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Space
Watching a new atmosphere form on an exoplanet

Robotics
How to build a machine that talks like you

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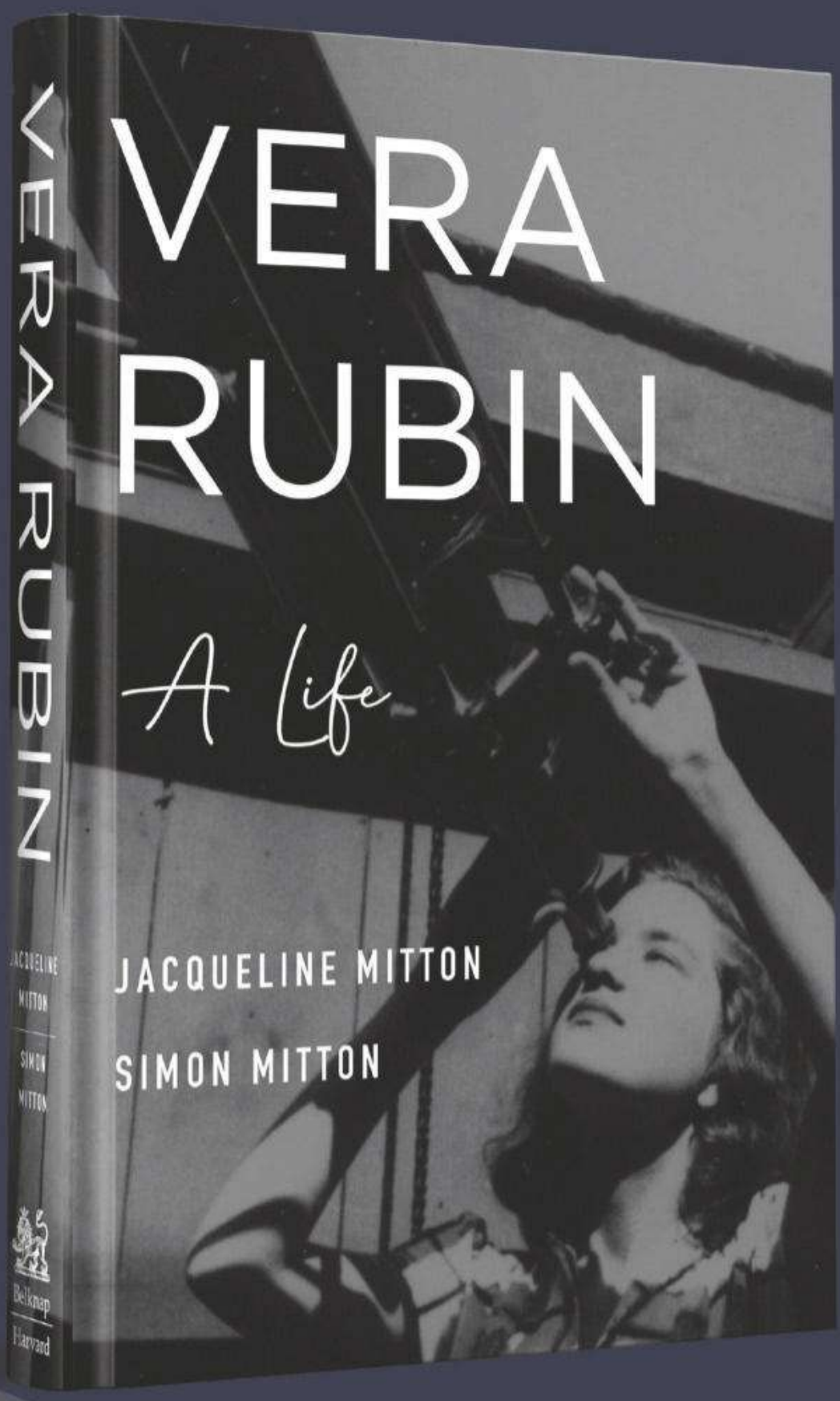

"This book firmly cements Rubin's place within the history of astronomy."

—Carolyn Collins Petersen, author of *The Discovery of the Universe*

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FROM THE EDITOR

Earlier this year, while most of us were scraping the bottom of the TV-streaming barrel to keep ourselves entertained during the third lockdown, Mars came to life. A fleet of spacecraft descended upon the Red Planet to learn its secrets, past and present. The missions arrived in convoy since Mars and Earth had practically rubbed shoulders the summer before, giving space agencies around the world the opportunity to make the shortest trip possible between the two planets.

Of all the missions, Perseverance and its daredevil descent to Martian soil garnered the most attention. It felt like the whole world was watching. The same was true a few years ago, as everyone waited for the New Horizons probe to switch back on as it approached its ultimate destination, Pluto. After all, who doesn't love a daring tale of exploration? Whether we're putting people on the Moon or taking a submarine to the bottom of the ocean, there are no bigger, more popular stories in science than those that take us to new frontiers.

So, inspired by the incredible tales of Martian exploration, we decided to dedicate this entire issue to the projects and missions that are pushing the boundaries of what we know and where we can go. From deep-sea mountains to deep space, we hope you enjoy this tour of what we think is some of the most mind-blowing science out there right now.

Daniel Bennett, Editor

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Join science writer Jheni for an expedition to a cave system deep within a mountain. Here, scientists are uncovering clues to the planet's climate past... and future. →p54

DR EZZY PEARSON
Humans are returning to the Moon, but this time we intend to do more than just collect soil. Space expert Ezzy takes us though our ambitious plans for the lunar landscape. →p60

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ON THE BBC THIS MONTH...

Greta Thunberg: A Year To Change The World
Follow the Swedish environmental activist as she explores the science of global warming and challenges world leaders to take action.
BBC One, starts mid-April, check *Radio Times* for details

CrowdScience: Why Does Grief Leave Me Feeling This Way?
Why have we evolved to be so affected by loss? Be it the death of a loved one, the end of a relationship or the loss of a job. Does grief serve any purpose? Or perhaps it's just the price we pay for being a social species with such strong connections.
BBC World Service, Friday 16 April, 8:30pm

Planet Defenders
Join a team of six dedicated young conservationists and filmmakers as they set out around the world to protect our planet and its amazing wildlife.
Catch it on BBC iPlayer

COVER: ANDY POTTS THIS PAGE: BBC X2, GETTY IMAGES, DANIEL BRIGHT

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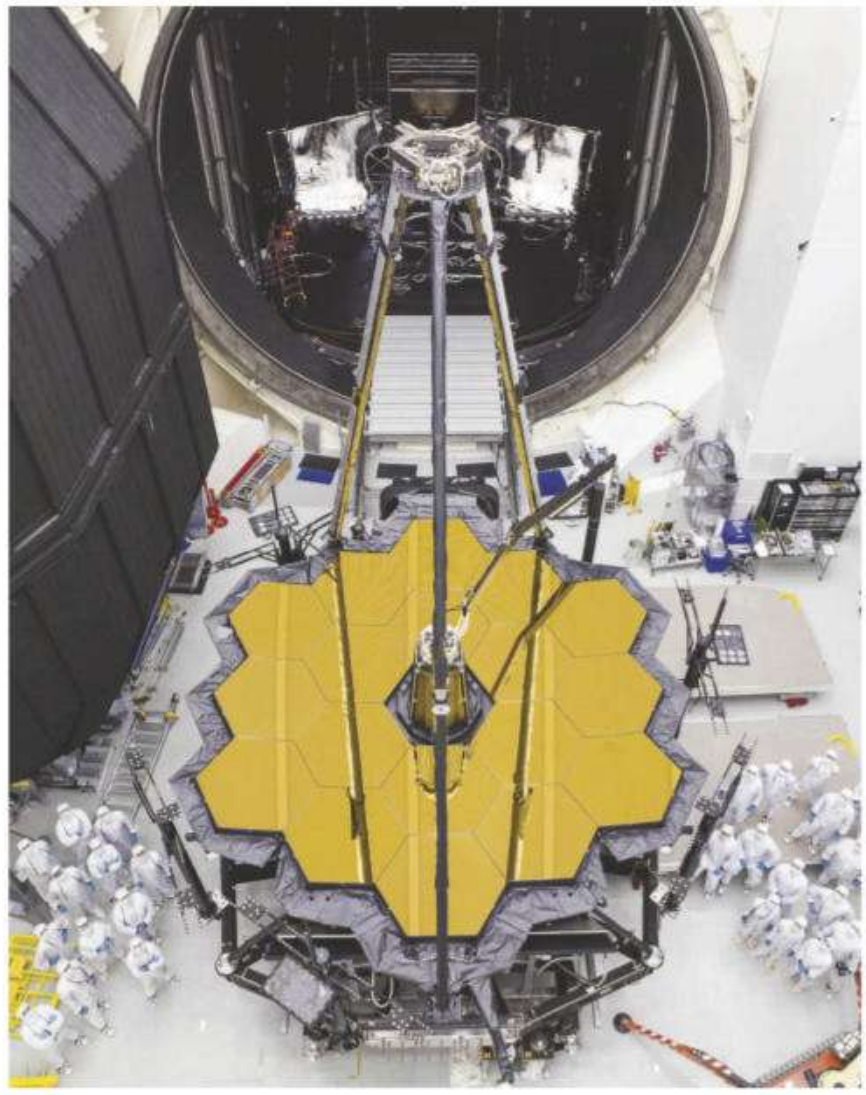

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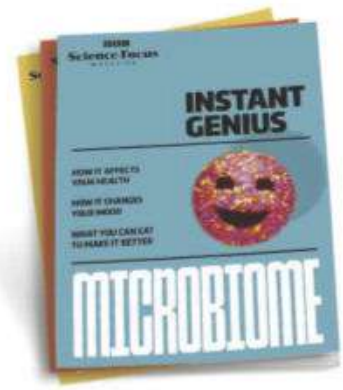

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EYE OPENER

Etna awakens

CATANIA, SICILY
ITALY

Mount Etna has done it again. In February, Europe's most active volcano erupted, releasing an estimated 40 million cubic metres of volcanic material and a 1,500-metre-high ash cloud.

"It's Etna's largest eruption since 2000 – and is very, *very* spectacular," says Boris Behncke, a volcanologist at Italy's National Institute of Geophysics. But while apocalyptic in appearance, the 3,300m-high volcano poses little danger to the local population and buildings (including the Mother Church of Belpasso, pictured). Etna's magma stream cools and solidifies well before reaching any towns. And unless crushed into dust by vehicles, any ash is too large to inhale.

"The volcano's regular eruptions are relatively safe and normal," says Becker. "In fact, the ash can be a valuable resource, used as a fertiliser or even building material. Everyone seems to want this stuff now – just not lying on the road!"

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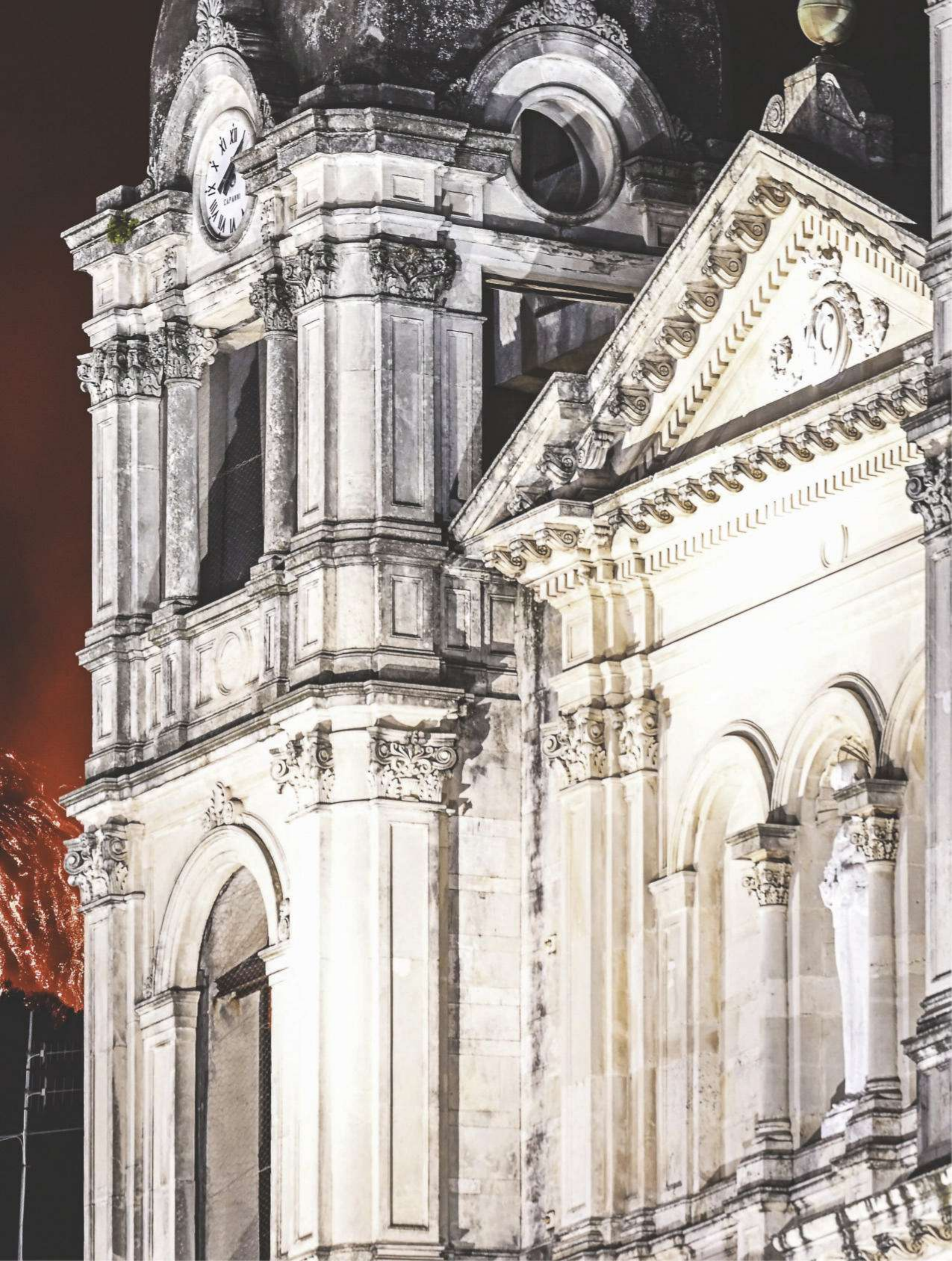

EYE OPENER

Flock exchange

LOUGH ENNELL
REPUBLIC OF IRELAND

Even seasoned nature photographers will squawk at this unique formation of starlings that, for a split-second, took the shape of a giant bird.

Called a murmuration, such a gathering occurs just before the starlings roost, each bird's superb senses preventing mid-air collisions. "They all keep space from one another with their incredible vision and reactions faster than our elite athletes," explains Prof Anne Goodenough from the University of Gloucestershire. "These abilities mean five million starlings have been known to fly in a murmuration."

However, this aerial display isn't for our benefit – starlings use murmurations to confound their enemies. As birds of prey hunt by focusing their vision on one individual, this unpredictable airborne swarm prevents predators from recognising a single starling. Overall, an ingenious defensive mechanism... Well, unless the murmuration takes the shape of one giant target.

JAMES CROMBIE/INPHO PHOTOGRAPHY

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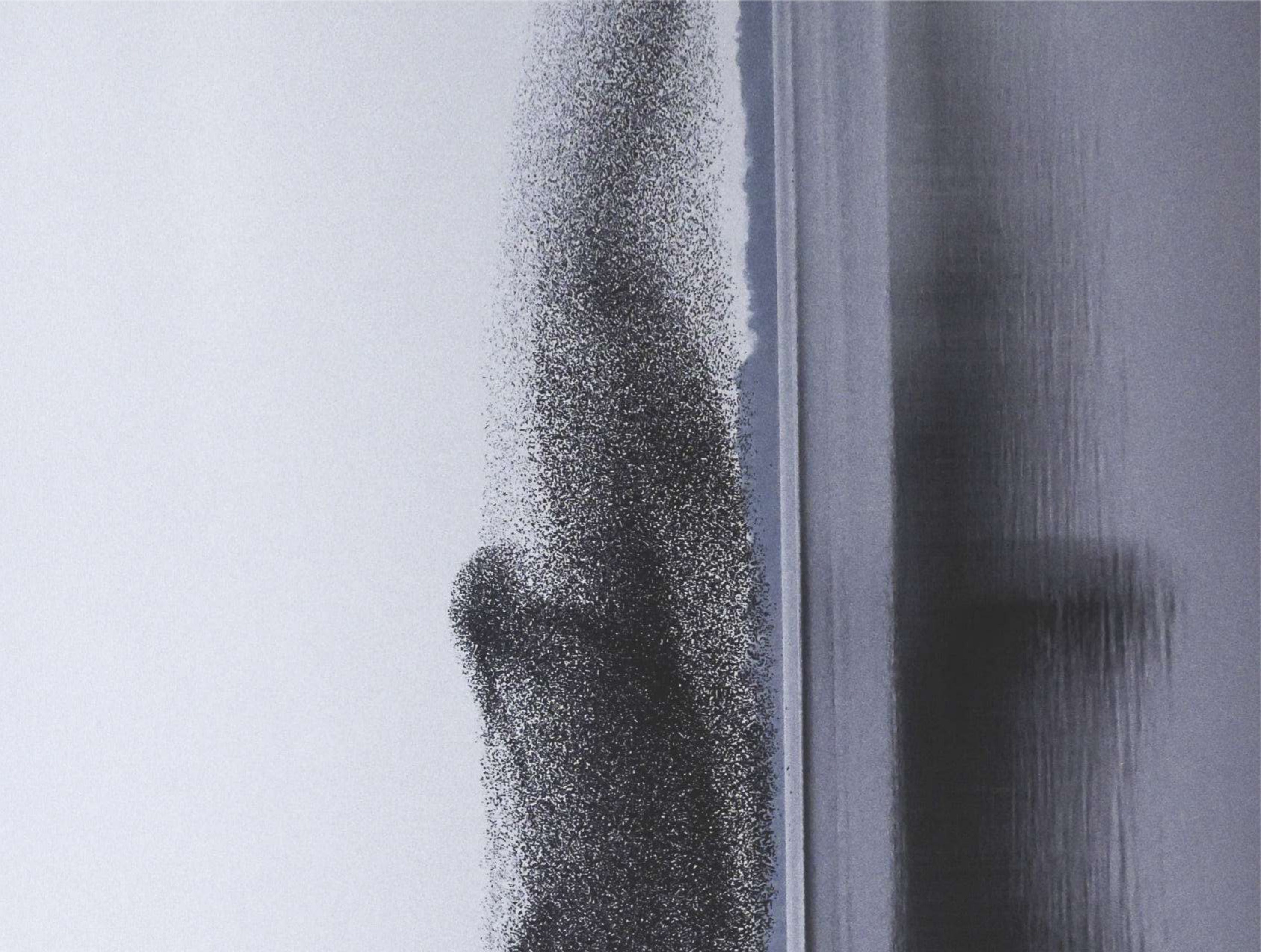

WASP
CRANE

EYE OPENER

Wasp's nest

RAVENNA, ITALY

Fancy living in one of these? It's a 3D-printed habitat called a 'TECLA'. The name comes from how it's built, a combination of TEchnology and CLAy, but its inspiration comes from nature – the potter wasp.

Potter wasps build tiny, pot-shaped nests for their larvae using a mix of soil and saliva. They chew the soil into a paste, then spit it out to construct the pot by coiling the paste around to form the sides and neck.

The TECLA's crane-sized printer follows a similar process, gradually printing a mix of clay from the site in an elaborate circular pattern, one 12mm-thick layer on top of another. "[We can] create the structure, roof and external cladding simultaneously," says Massimo Moretti, founder of WASP (World's Advanced Saving Project), the company behind the TECLA. "It's biodegradable, but treating it with a hydrophobic coating stops it decomposing while it's in use. If it's properly maintained, the structure is infinite."

TECLA

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CONVERSATION

YOUR OPINIONS ON SCIENCE, TECHNOLOGY AND *BBC SCIENCE FOCUS*

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LETTER OF THE MONTH

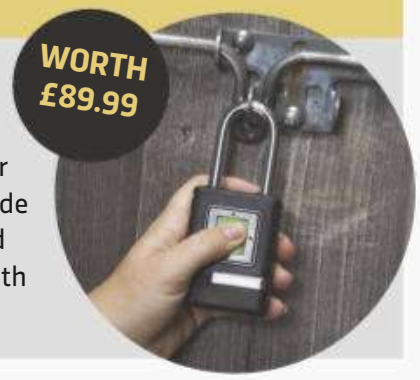
Where you left it

The February issue's *Explainer* (p86) on memory pointed out how it's all too easy to forget where you left things like your car keys if you don't pay sufficient attention when you put them down. But there's a way to solve this problem: decide on specific places to leave these items, then discipline yourself to only leave them in their designated spots. If you live with other people, pick places that your housemates won't disturb. If you keep putting your 'loseables' in these locations, it'll eventually become a habit and you'll always know where to find them!
Paul Jeffels, Derby

PS: I've subscribed to *BBC Science Focus* for years and the 'How your brain creates reality' feature (p54, February) is one of the most interesting – and probably controversial – that you've ever printed. Thank you!

Great suggestion, Paul! The only trouble is after 12 months of being cooped up indoors, the thing I most often lose is my patience.
Daniel Bennett, Editor

WRITE IN AND WIN!
The writer of next issue's *Letter Of The Month* wins a **Master Lock Biometric Padlock**. It can store fingerprints for two main users and eight additional people. The 56mm-wide padlock has a 9mm-diameter shackle and, when combined with a chain, can be the ideal solution if you share a bike with other people. **masterlock.eu**

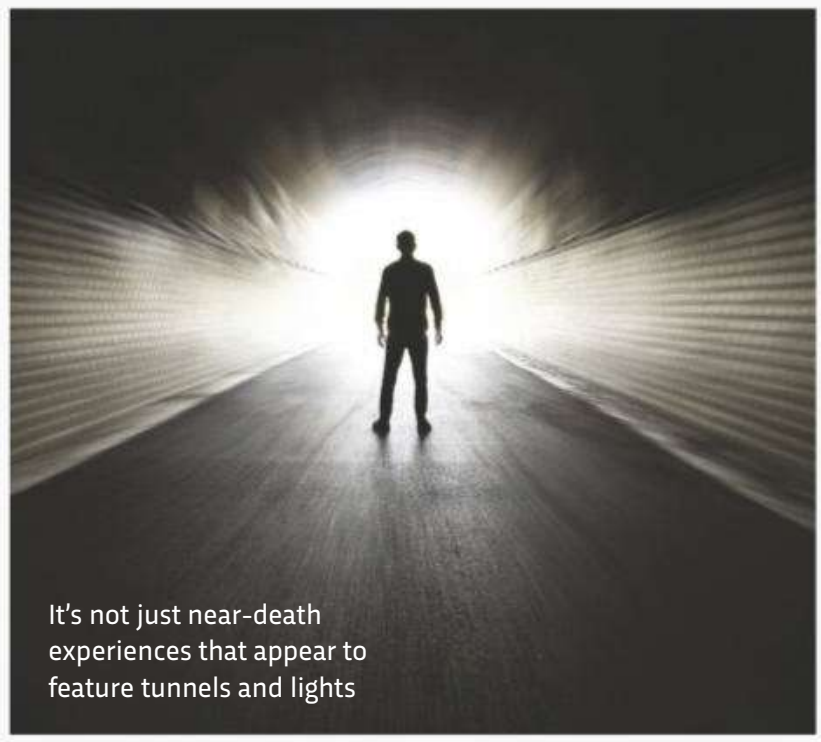


Tunnel vision

I read Dr Susan Blackmore's answer to the question 'Do people in a coma dream?' on your website recently. I thought you might like to hear my experience.

Many years ago, I was in a coma for a month and a half, but right before I woke up, I remember finding myself in a tunnel. There was a bright light at the end, which I walked towards and when I emerged, I found a big golden gate. The gate opened and I walked through into a playground filled with children my age, who were laughing and happy. It all felt too good to be true though, so I turned to leave. Then two huge men approached me, took hold of my hands and tried to lead me back into the playground. I let go and ran back towards the gate, but they stopped me and tried to pull me back. I grabbed the gate, but they wouldn't let me go. We struggled for a while, but eventually they gave up and walked away, at which point I awoke from my coma.

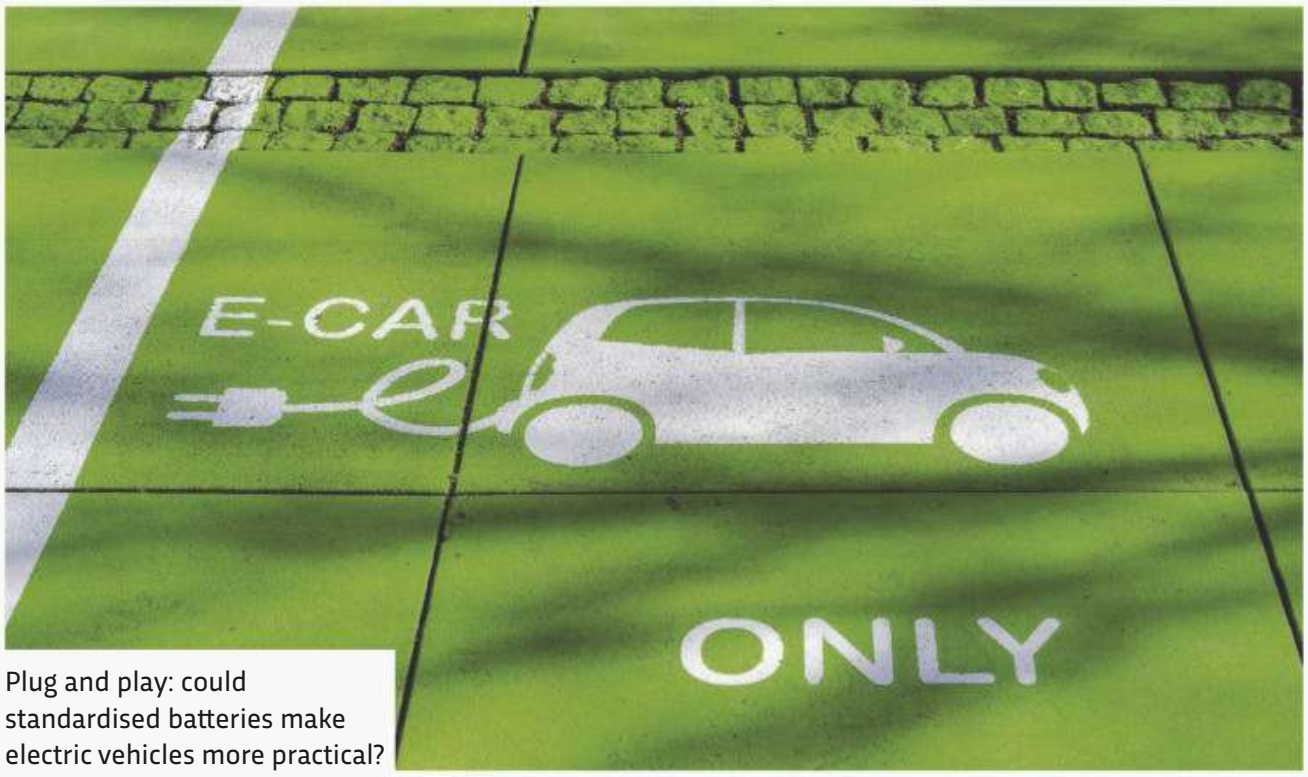
I hope my story helps answer the question of whether people in comas dream.
Ghulam Shahban, via email



It's not just near-death experiences that appear to feature tunnels and lights

"I CAN'T WAIT TO SEE WHAT THE SURFACE OF THE ASTEROID PSYCHE LOOKS LIKE. IT COULD BE REALLY QUITE UNUSUAL AND STRANGE. I'M HOPING THAT IT'LL LOOK TOTALLY BIZARRE"

DR LINDY ELKINS-TANTON, P66



Plug and play: could standardised batteries make electric vehicles more practical?

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More horsepower

Thank you for the story in February's edition about the new fast-charging batteries for electric cars (*Innovations*, p40). It made me wonder why electric car manufacturers don't agree to use standardised batteries that are compatible with more types of vehicles. That way batteries could be easily replaced – they could even be interchangeable. Following the pattern of stagecoaches and horses, batteries could be swapped over at 'filling stations' when they're running low and left to recharge for the next customer. Filling stations would find a new lease of life and would only need to carry a few different models of batteries.

Perhaps there are good, technical reasons why this isn't possible, but it would be interesting to know what they are.

Richard Lindley, via email

Not a rat's chance

Henry Nicholls's story on rats in the March issue (*Reality Check*, p32) neglected to mention two facts I recently read about in the general media. First, rats in London and other urban areas have dramatically increased in size over recent years. And second, if it weren't for urban foxes the rats would also have increased in numbers.

Much of the statistical evidence in Nicholls's story relates to the lockdown in Manhattan, which may or may not apply in the UK. The only solid research done here was apparently in the 1990s and showed that rats were not healthy creatures to live with.

Dare I suggest that *BBC Science Focus* would be a suitable platform to gather together whatever research has been done on rats in the UK and produce a definitive article on the subject in a future edition. It's often said that nobody is ever more than a few yards from a rat so the subject should interest most of us!

David Whitaker, Hampshire

A rat research project would interest us too. Some of the *BBC Science Focus* team have had rats in the past (as pets). One of us still does!

Daniel Bennett, Editor

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DISCOVERIES

HUBBLE SPOTS NEW ATMOSPHERE FORMING ON EARTH-LIKE EXOPLANET

The planet may have lost its previous atmosphere and is now forming a new one, thanks to volcanic activity

NASA/ESA/R HURT

Size matters Teenage *T. rexes* distort dinosaur size diversity p22 **Clearly useful** The high-tech contact lens that monitors your eye health p23 **Off with my head!** Sea slugs lose their heads... but live on to grow new bodies p24

A wide-field view, showing the region of sky in which the exoplanet Gliese 1132 b can be found. Inside the yellow circle is a red dot – that's the star Gliese 1132 around which Gliese 1132 b orbits

For the first time, scientists using the Hubble Space Telescope have found evidence of volcanic activity reforming the atmosphere on a rocky planet around a distant star.

The planet, Gliese 1132 b, is located 40 light-years away in the constellation Vela and has a similar density, size and age to Earth.

It was first discovered in 2015 by the MEarth-South telescope array in Chile and appears to have begun life as a so-called sub-Neptune planet – a gaseous world with a thick atmosphere.

It's thought Gliese 1132 b initially had a radius several times that of Earth, but its primordial hydrogen and helium atmosphere was rapidly stripped away by the intense radiation from its hot, young star. The stripping process left behind a bare core approximately the same size as Earth.

Now, based on new observations carried out by Hubble, researchers have discovered that a second atmosphere, rich in hydrogen, hydrogen cyanide, methane and ammonia, may have formed on the planet due to volcanic activity.

They theorise that this arose due to hydrogen from the original atmosphere being absorbed into the planet's molten magma mantle and then slowly released to form a new atmosphere. Though this second atmosphere is also leaking away into space, it's continually being replenished from the reservoir of hydrogen in the mantle, they say.

"Further opportunities to observe Gliese 1132 b may come via the James Webb Space Telescope"

"This second atmosphere comes from the surface and interior of the planet, and so it's a window onto the geology of another world," said team member Dr Paul Rimmer of the University of Cambridge. "A lot more work needs to be done to properly look through it, but the discovery of this window is of great importance."

Further opportunities to investigate the geology of Gliese 1132 b may come via the James Webb Space Telescope (JWST) – the successor to Hubble, due to launch in October (see p32 for more on the JWST's preparations for lift-off).

The JWST will primarily look at the Universe in infrared, allowing it to see more distant objects than Hubble, which tends to observe in optical and ultraviolet wavelengths. This is due to the light from more distant objects being more redshifted – pushed from the UV and optical parts of the spectrum towards the near-infrared.

"This atmosphere, if it's thin – meaning if it has a surface pressure similar to Earth – probably means you can see right down to the ground at infrared wavelengths. That means that if astronomers use the JWST to observe this planet, there's a possibility that they'll see not the spectrum of the atmosphere, but rather the spectrum of the surface," said team leader Mark Swain of the Jet Propulsion Laboratory. "And if there are magma pools or volcanism going on, those areas will be hotter. That will generate more emissions and so they'll potentially be looking at the actual geological activity, which is exciting!"

CLIMATE

Frozen plant fossils hint at catastrophic future ice melts

Long-lost ice core provides evidence of a massive melt during a previous period of warming

If the Greenland ice sheet were to melt away, global sea levels would rise an average of six metres, putting almost every coastal city in the world at risk of major flooding.

Now, a study of an ice core forgotten for more than 50 years has found this is exactly what happened during a recent warm period that was alarmingly similar to the one we're headed towards due to human-caused climate change.

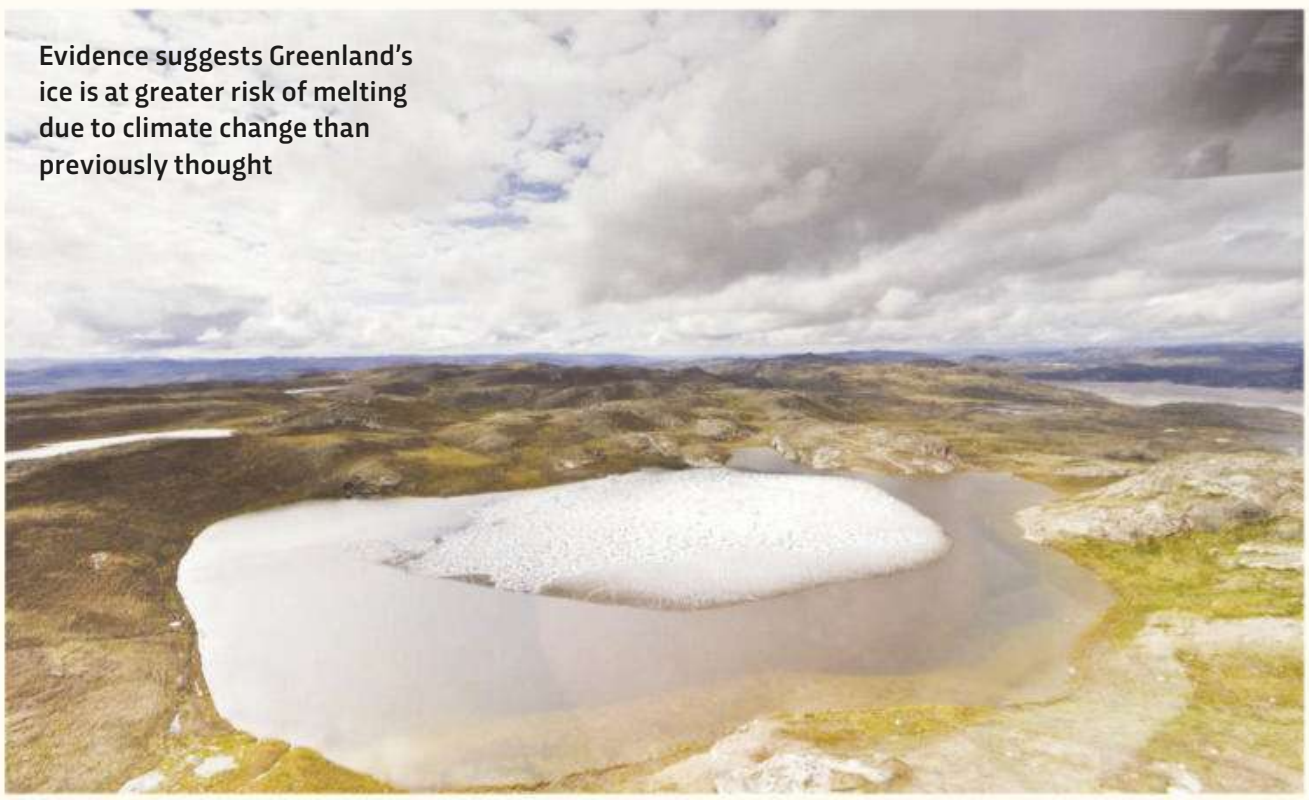
The core was originally extracted in 1966 from Camp Century, a Cold War military base. The base masqueraded as a science station to provide cover for Project Iceworm – a secret US Army programme to build a network of mobile nuclear missile launch sites beneath the Greenland ice sheet. The military mission failed, but the science team did complete important research, including drilling a 1,400m-deep ice core.

The core was kept in an army freezer before being moved to New York's University of Buffalo in the 1970s, and then to the University of Copenhagen in the 1990s, before eventually being rediscovered by Danish researchers in 2017.

For the last year, an international team of scientists have been analysing the plant fossils and sediment found in the core to determine its composition and age. They concluded that most, if not all, of Greenland melted at least once during the past million years and was covered in a blanket of vegetation including moss, lichen, and perhaps even spruce and fir trees.

"Ice sheets typically pulverise and destroy everything in their path," said team member Dr Andrew Christ, of the University of Vermont. "But what we discovered was delicate plant structures – perfectly preserved. They're fossils, but they look like they died yesterday. It's a time capsule of what used to live on Greenland that we wouldn't be able to find anywhere else."

"Our study shows that Greenland is much more sensitive to natural climate warming than we used to think – and we already know that humanity's out-of-control warming of the planet hugely exceeds the natural rate," said Christ.



Evidence suggests Greenland's ice is at greater risk of melting due to climate change than previously thought

DAVIDE DE MARTIN/ESA/HUBBLE, DIGITIZED SKY SURVEY 2, JOSHUA BROWN/UVM ILLUSTRATIONS: KYLE SMART

CHATTERBOXES

A study of 800 people carried out at Cornell University found that, on average, they wished that their recent conversations had lasted almost two minutes longer.

THE FUTURE

The pandemic has made the last year tough for everyone. But there's at least one silver lining: a survey of 1,000 11- to 17-year-olds, for digital healthcare provider Medicspot, has found that almost half of them are now interested in pursuing a career in STEM.

Good month

Bad month

MOTHS

The UK's moths have declined by a third in the last 50 years, a survey by Butterfly Conservation has found. They blame artificial light, pollution and climate change, along with a loss of habitat.

CAT 'OWNERS'

Researchers at Kyoto University had cats watch their owners ask another person for help opening a container. Some people offered help, while others didn't. In both cases they offered food to the cat afterwards. Unlike dogs, who preferred not to take food from the unhelpful people, the cats scoffed the food regardless of who offered it.

In numbers

70
years old

The age of a Laysan albatross called Wisdom living on the Midway Atoll in the Pacific. Wisdom is the world's oldest known wild bird and has just hatched her 40th chick.

200
days

The length of time researchers living in China's sealed Yuegong-1 biosphere were able to generate oxygen, water and food without help from the outside world.

3

Eating meat three or more times a week can increase the risk of various illnesses, including heart disease, pneumonia and diabetes, a study at the University of Oxford has found.

ZOOLOGY

Cuttlefish exercise self-control, demonstrating a link between willpower and intelligence

The quick-learning cephalopods proved their intelligence in an adapted version of the Stanford marshmallow experiment

Cuttlefish not only possess three hearts and a 360° field of vision, but also a strong sense of self-control, according to a new study.

As research from the Marine Biological Laboratory in Massachusetts shows, when presented with the option of eating a raw king prawn immediately or a grass shrimp (their preferred food) after a short delay, the marine molluscs chose the latter option. In fact, while all six cuttlefish tested could tolerate a delay in feeding of 15 seconds, some were prepared to wait 130 seconds. These results indicate the cephalopods can delay gratification like large-brained vertebrates, such as chimps.

The cuttlefish that could wait longest before eating its favourite food also performed better in a cognitive test, learning faster to associate a visual cue with a food reward.

If this experiment sounds familiar, it's because it's based on the famous Stanford marshmallow experiment, which gave children the choice of getting an immediate reward (one marshmallow) or a better, delayed treat (two marshmallows). However, while it's relatively easy to explain the test to human participants, communicating the idea to cuttlefish was more complex.

At first, the invertebrates were placed in an aquarium leading to two chambers marked with one of three symbols representing immediate gratification, delayed gratification and 'inaccessible'. To help them learn the concepts, the same food was added to each chamber. After a while, the cuttlefish appeared to understand that each chamber followed a different rule, so researchers could use different treats in the experiment.

"Cuttlefish spend most of their time camouflaging, sitting and waiting, punctuated by brief periods of foraging," said lead researcher Dr Alexandra Schnell. "They break camouflage when they forage, so they're exposed to every predator in the ocean. We speculate that delayed gratification may have evolved as a by-product of this, so the cuttlefish can optimise foraging by waiting to choose better quality food."

Cuttlefish have one of the largest brain-to-body ratios of all invertebrates. The cephalopods can also change their appearance in less than a second to blend into the background.

ROGER HANLON, ALAMY, MERCEDES CONDE-VALVERDE

PALAEONTOLOGY

Neanderthals could talk like humans, study suggests

Humans were once thought to have spoken language unlike any other species on Earth. But now, scientists think Neanderthals also had the ability to hear and produce speech just like us.

"For decades, one of the central questions in human evolutionary studies has been whether the human form of communication, spoken language, was also present in any other species of human ancestor, especially the Neanderthals," said Prof Juan Luis Arsuaga at the Universidad Complutense de Madrid, a co-author of the study.

The international team of researchers studied the auditory capacities of Neanderthals, *Homo sapiens* and ancestors of Neanderthals from the archaeological site Atapuerca in Spain.

By using high-resolution CT scans, they created virtual 3D replicas of the ear structures of each species to model the frequencies that they could hear the best. The human ear can hear sounds between frequencies of 20Hz and 20kHz, but the majority of human speech sounds are up to 5kHz. Neanderthals showed a greater sensitivity in the frequency range of 4-5kHz than their ancestors from Atapuerca, similar to *H. sapiens*.

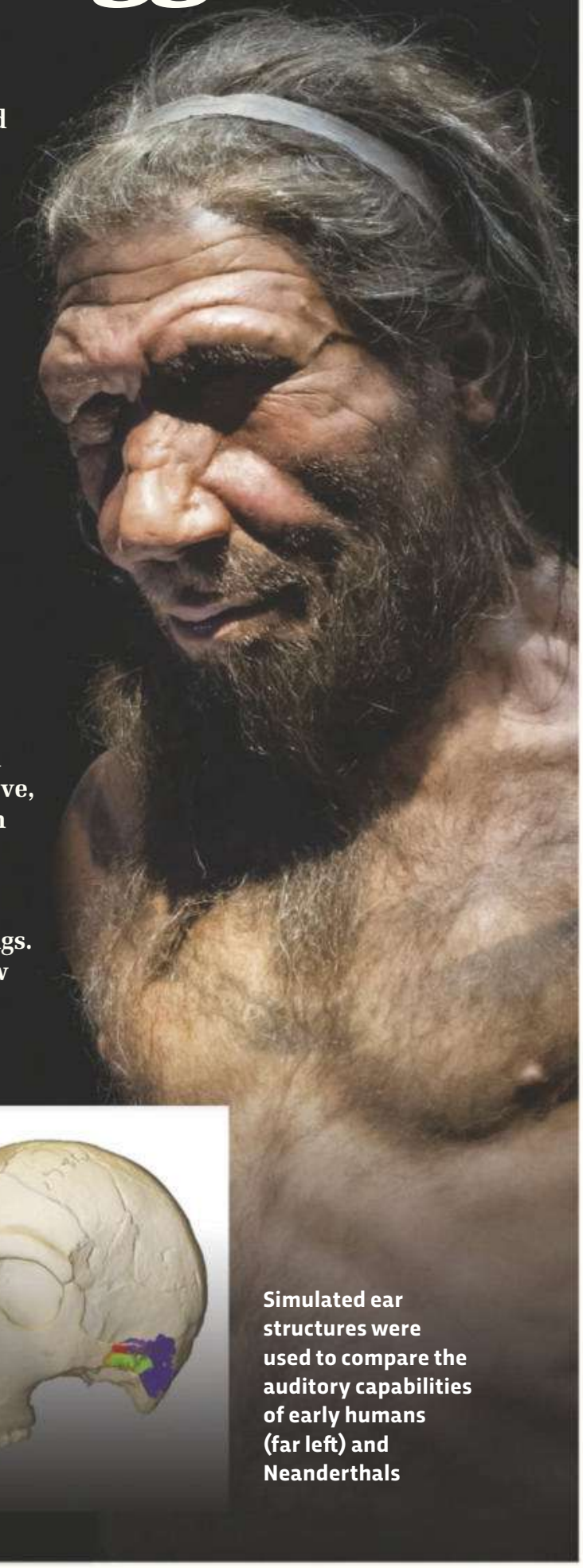
The researchers also looked at the 'occupied bandwidth' of each species: the range of frequencies to which the ear is most sensitive. A wider occupied bandwidth means the species can distinguish a broader range of sounds, and so communicate more effectively. Neanderthals' occupied bandwidth was wider than their ancestors' and similar to *H. sapiens*.

The fact that Neanderthals had hearing tuned to human speech, which hadn't been evolved by their ancestors in Atapuerca, suggests they had the capacity for speech too.

"The presence of similar hearing abilities, particularly the bandwidth, demonstrates that the Neanderthals possessed a communication system that was as complex and efficient as modern human speech," said Prof Mercedes Conde-Valverde at the Universidad de Alcalá in Spain, lead author of the study.

Neanderthals could even have had a form of language, the researchers believe, although that doesn't necessarily mean they had the mental faculties to speak the same language as ancient humans.

Prof Rolf Quam, a co-author of the study, is confident in the study's findings. "The results are solid and clearly show the Neanderthals had the capacity to perceive and produce human speech."



"Neanderthals could even have had a form of language"

Simulated ear structures were used to compare the auditory capabilities of early humans (far left) and Neanderthals

NEUROSCIENCE

Lab-grown organoids shed light on great apes' brain growth

'Mini brains' provide clues to size difference in human, gorilla and chimpanzees' brains

One of the key characteristics that sets humans apart from other apes, such as gorillas and chimps, is the size of our brains. Human brains are much larger and contain up to three times as many neurons. Uncovering the cause behind this difference in brain development has long proven difficult for scientists.

But now, a team at the Medical Research Council (MRC) Laboratory of Molecular Biology in Cambridge, UK, might have found the answer. And they discovered it by using brain 'organoids' (miniature, simplified versions of the organs) grown from stem cells taken from humans, gorillas and chimpanzees.

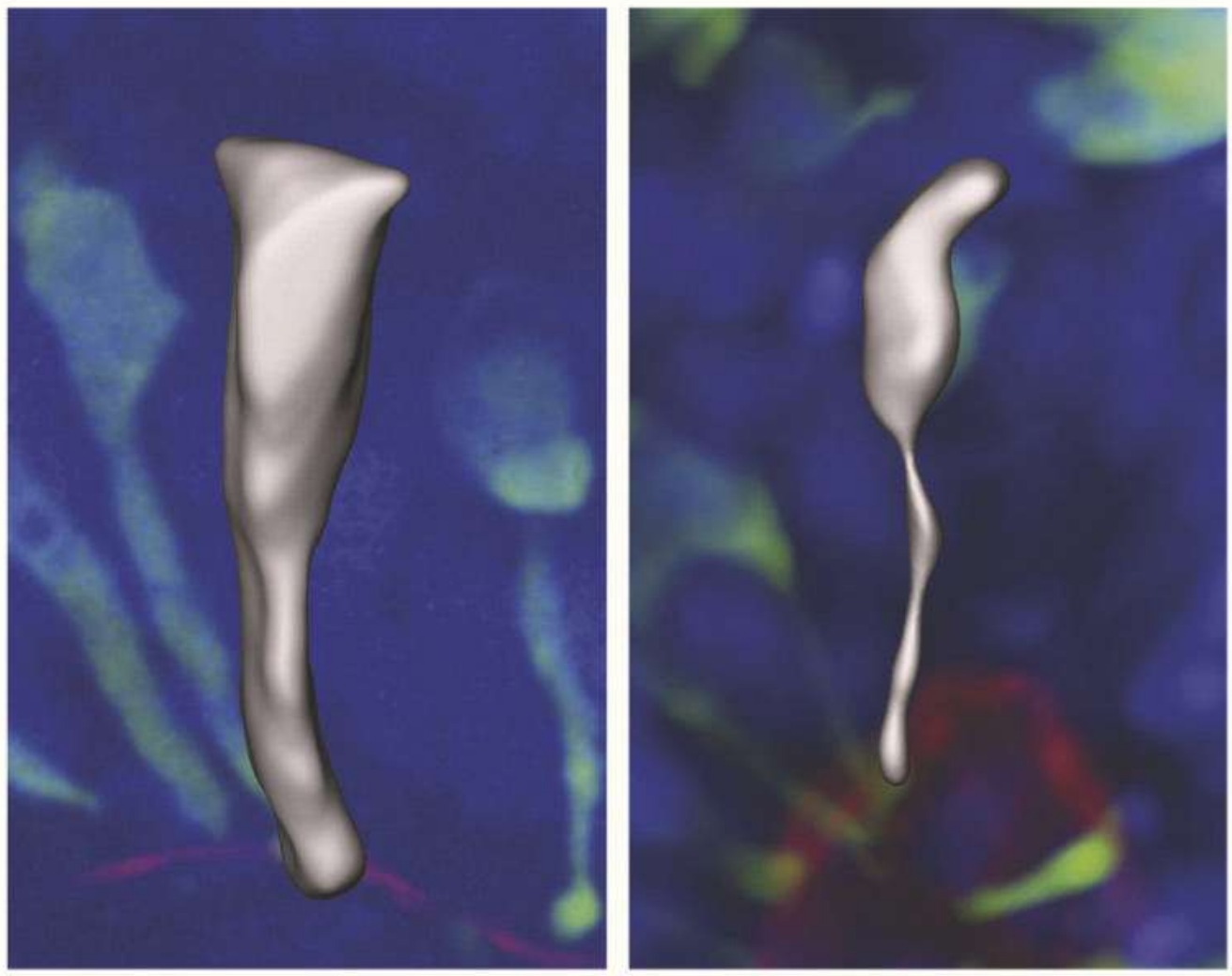
During the early stages of brain development, neurons are made by stem cells called neural progenitors. These progenitor cells initially have a cylindrical shape that makes it easy for them to split into identical daughter cells with the same shape. But as they mature and slow their multiplication, the cells elongate to gradually form a shape resembling a stretched ice-cream cone.

Previous research in mice has found that this process occurs over the course of a few hours. In the new study, the researchers found that the process takes around five days in gorillas and chimpanzees, but around seven in humans. This extra time allows the human cells to produce more neurons, the researchers say.

"We've found that a delayed change in the shape of cells in the early brain is enough to change the course of development, helping determine the numbers of neurons that are made," said study leader Dr Madeline Lancaster. "It's remarkable that a relatively simple evolutionary change in cell shape could have major consequences in brain evolution. I feel like we've really learnt something fundamental about the question I've been interested in for as long as I can remember: what makes us human?"

To uncover the genetic mechanism driving these differences, the researchers compared gene expression – which genes are turned on or off – in the human brain organoids versus those of the other apes. They found differences in a gene called ZEB2, which was turned on sooner in gorilla brain organoids than in the human organoids. Turning this gene on sooner in the human brain organoids led to them developing in a more gorilla-like way, while turning it on later led the gorilla organoids to develop in a more human-like way.

> **"The cells elongate to gradually form a shape resembling a stretched ice-cream cone"**



Human progenitor cells (left) remain cylindrical after five days, while a gorilla's (right) have grown into a 'cone'

S BENITO-KWIECINSKI/MRC LMB/CELL, DLR

Test participants get spun on a centrifuge to mimic artificial gravity

PSYCHIATRY

Weightlessness could decrease astronauts' ability to recognise emotions in crew mates

Being cooped up in a tin can that's flying through space with a bunch of strangers is likely to put a strain on anyone. But now researchers at the University of Pennsylvania have found that weightlessness could reduce astronauts' ability to recognise emotions.

Over 60 days, the researchers had 24 participants spend all their time lying in a bed tilted at a 6° angle towards their heads to simulate microgravity, except for 30 minutes a day in which they were spun on a centrifuge with their head at the centre to mimic artificial gravity. Their cognitive performance was assessed before, during and after the bed rest, using tests that measured differences in their spatial orientation, memory, risk taking, and emotion recognition that were specifically designed to determine the performance of astronauts on the International Space Station.

The researchers found that the participants' cognitive speed dropped once they went into simulated microgravity, but then stayed the same for the rest of the experiment. However, they got persistently slower at recognising emotions and were more likely to identify facial expressions as angry than happy or neutral.

"Astronauts on long space missions, very much like our research participants, will spend extended durations in microgravity, confined to a small space with few other astronauts," said Prof Mathias Basner, from the University of Pennsylvania Perelman School of Medicine. "The astronauts' ability to correctly 'read' each other's emotional expressions will be of paramount importance for effective teamwork and mission success. Our findings suggest that their ability to do this may be impaired over time."

The effect might not be due to the simulated microgravity, though. It could be due to the participants being socially isolated over the study period.

"We cannot say whether the effects observed on the emotion recognition test were induced by simulated microgravity or by the confinement and isolation inherent to the study, with separate bedrooms and sporadic contact to the study team," said Dr Alexander Stahn, a co-author of the study. "Future studies will need to disentangle these effects."

In the future, the team plans to study whether longer periods of artificial gravity or a different amount of socialisation could solve these issues.

Fossilised specimens of tyrannosaurs (clockwise from top left): an adult *T. rex*; a juvenile *T. rex*; an adult *Tarbosaurus bataar*; and *Raptorex kriegsteini*

PALAEONTOLOGY

Teenage *T. rexes* bested smaller rivals

The theory could explain why medium-sized dino fossils are so rare

Prehistoric heavyweights such as the *Tyrannosaurus rex* might have outcompeted their smaller rivals while in their teens, leaving medium-sized dinosaurs missing from the fossil record, researchers from the University of New Mexico and the University of Nebraska-Lincoln believe.

Palaeontologists have long been puzzled as to why the global diversity of dinosaurs, particularly small- to medium-sized species, is so low. Now, a new study published in the journal *Science* suggests this may be because the smaller species were outcompeted by adolescent megatheropods (big, bipedal, carnivorous dinosaurs) that were not yet fully grown.

Despite growing to the size of double-decker buses, dinosaurs such as the *T. rex* started life relatively small – about the size of a Chihuahua – on account of having to hatch from eggs. Hence, it's likely they would have had to compete with smaller dinosaurs as they grew, the researchers say.

"We wanted to test the idea that dinosaurs might be taking on the roles of multiple species as they grew, limiting the number of actual species that could co-exist in a community," said Kat Schroeder, a graduate student who led the study.

"Dinosaur communities were like shopping malls on a Saturday afternoon: jam-packed with teenagers. They made up a significant portion of the

“Dinosaur communities were like shopping malls on a Saturday afternoon”

individuals in a species and would have had a very real impact on the resources available in communities.”

To investigate the question of decreased dinosaur diversity, the team gathered data from locations around the globe where fossils from more than 550 dinosaur species had been found. They then organised the dinosaurs by mass, diet, size and location.

With this information, they were able to get an idea of what the dinosaur communities would have looked like by combining data from growth rates (indicated by lines found in cross-sections of bones) and the number of infants surviving each year, based on the fossil record. The team then worked out what proportion of a megatheropod species would have been juveniles.

“There is a gap – very few carnivorous dinosaurs between 100kg to 1,000kg exist in communities that have megatheropods,” said Schroeder. “And the juveniles of those megatheropods fit right into it.”

They also found that the gap was much smaller in Jurassic communities, which ran from 200 to 145 million years ago, than Cretaceous communities, which ran from 145 to 65 million years ago, when the *T. rex* was king.

“Jurassic megatheropods don’t change as much – the teenagers are more like the adults, which leaves more room in the community for multiple families of megatheropods as well as some smaller carnivores,” said Schroeder. “The Cretaceous, on the other hand, is completely dominated by tyrannosaurs and abelisaurs, which change a lot as they grow.”

MEDICINE

Smart contact lenses may soon monitor your eye health in real time

The technology has been awarded a patent and will soon be ready for clinical trials

Researchers from Purdue University in the US have successfully fitted stretchable biosensors to a commercially available contact lens for the first time. The breakthrough will enable them to gather vital information about patients’ eye health without discomfort, or the need for anaesthetics or other intrusive surgical measures.

“This technology will be greatly beneficial to the painless diagnosis or early detection of many ocular diseases including glaucoma,” said lead researcher Prof Chi Hwan Lee. “Since the first conceptual invention by Leonardo da Vinci, there has been a great desire to utilise contact lenses for eye-wearable biomedical platforms.”

Fitting sensors or other electronics to commercial soft contact lenses has previously proven difficult due to the complex fabrication techniques required to embed them into a flexible, curved contact lens.

Now, a multidisciplinary group of biomedical, chemical and mechanical engineers based at Purdue have figured out a method of doing so using a combination of printing, electroplating and water-soluble bonding techniques.

The sensors embedded in the lenses can then be connected to a computer via a thin wire and used to record the electrical activity in the retina by detecting minute changes in its sensitivity to light.

The new technology has been awarded a patent and the researchers are now looking to begin testing it in clinical trials.

“This technology will allow doctors and scientists to better understand spontaneous retinal activity with significantly improved accuracy, reliability and user comfort,” said clinical lead Prof Pete Kollbaum, the director of the Borish Center for Ophthalmic Research.

CHI HWAN LEE/PURDUE UNIVERSITY, FIELD MUSEUM OF NATURAL HISTORY/R HOLIS/P SERENO/ANDRE ROWE

Newly developed smart contacts let doctors see how healthy your eyes are

BIOLOGY

Scientists grow tear glands in a lab – before making them cry

The 'organoids' teared up as part of a study looking to stop dry eye diseases

Researchers in the Netherlands have grown tear glands in a lab – and then made them cry. Don't worry, this isn't the result of evil scientists with too much time on their hands; the cluster of cells was created to help the researchers understand eye diseases.

Using stem cells and a cocktail of growth factors, experts at University Medical Centre Utrecht were able to build tear 'organoids' – a three-dimensional collection of cells designed to resemble miniature tear glands (also known as lacrimal glands). In order to mimic the wetness of the human eye, these organoids were suspended in liquid.

In humans, tear production is controlled by nerves which release neurotransmitters that trigger the secretion of tears. The scientists soon discovered that the glands reacted to the same neurotransmitters, but as the organoids lacked ducts to secrete the tears, they swelled up like balloons and some ruptured. Once transplanted into mice, however, the organoids eventually developed duct-like structures.

"Further experiments revealed that different cells in the tear gland make different components of tears. And these cells respond differently to tear-inducing stimuli," said Dr Yorick Post, who took part in the project.

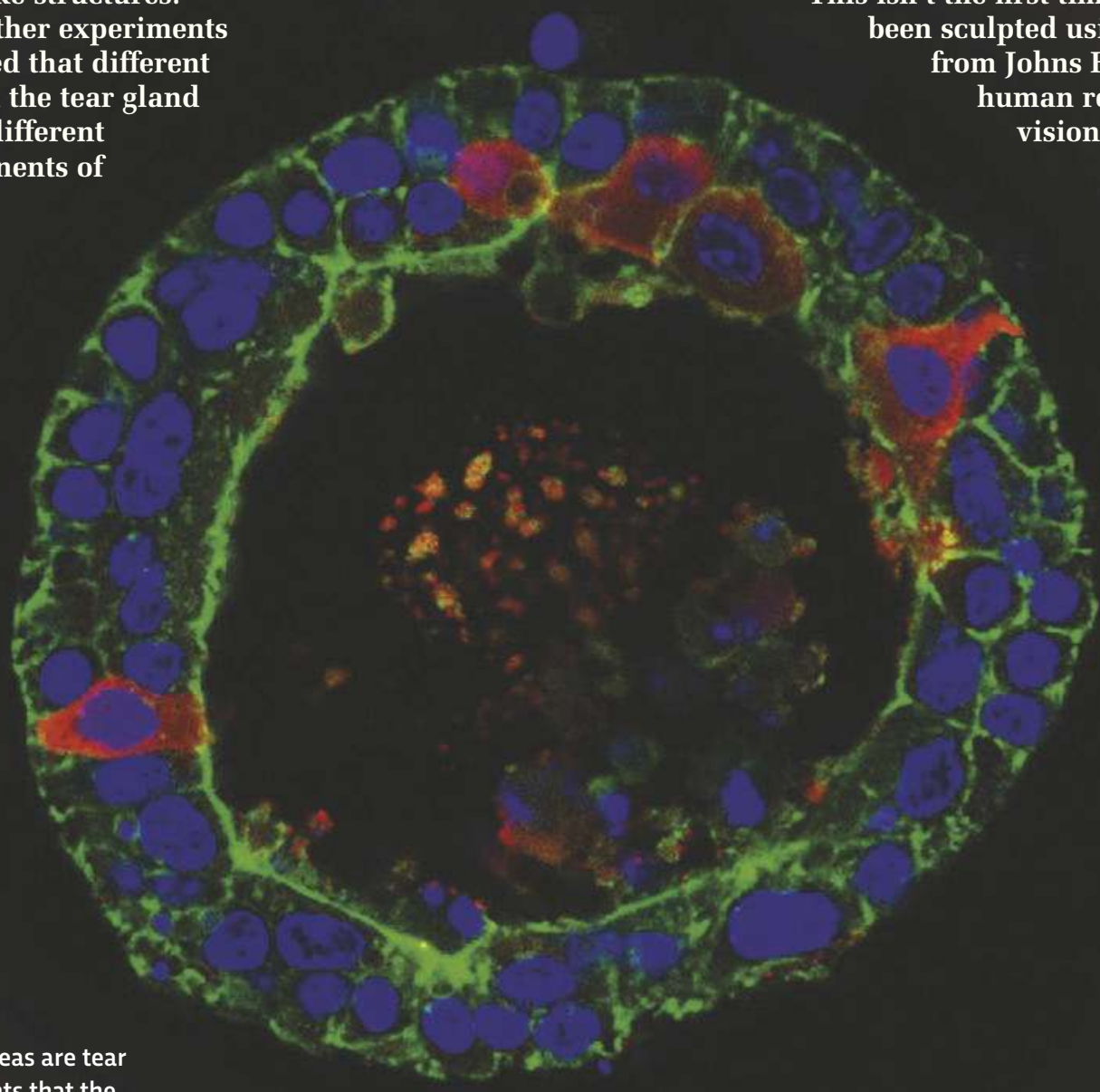
Tear glands aren't only useful to convey emotions in humans, but they also lubricate the eye, providing a protective layer of liquid over the cornea. Unhealthy glands can therefore lead to serious medical problems.

"Dysfunction of the tear gland, for example in Sjögren's syndrome, can have serious consequences, including dryness of the eye or even ulceration of the cornea. This can, in severe cases, lead to blindness," said Dr Rachel Kalmann, ophthalmologist and researcher on the project.

It's hoped the development of the tear organoids can help when it comes to testing new drugs and will enable scientists to understand how cancers in the gland form.

"Hopefully in the future, this type of organoid may even be transplantable to patients with non-functioning tear glands," added PhD student Marie Bannier-Hélaouët, who worked on the project.

This isn't the first time that sections of the eye have been sculpted using stem cells. In 2018, a team from Johns Hopkins University in the US grew human retinas to investigate how colour vision in humans developed.



The red areas are tear components that the organoid 'cried'

"Hopefully in the future, this type of organoid may even be transplantable"

While the head was able to heal and grow a new body, the body did not grow a new head

They did what?

MC Hammer's 1990 hit *U Can't Touch This* played to baby fish

WHAT DID THEY DO?
Rebecca Poulsen, a DJ and neuroscientist at the University of Queensland, Australia, played MC Hammer's 1990 floor-filler *U Can't Touch This* to a group of juvenile zebrafish and monitored their brain activity using a special microscope.

WHY DID THEY DO THAT?
She wanted to investigate how the fishes' young brains responded to a range of different sounds, tones and frequencies, and to study how their sound-processing ability changes as they grow into adults.

WHAT DID THEY FIND?
They found that the fish were able to hear a much broader range of frequencies than previously expected and that neurons in their brains appeared to be reacting to the beat and vocals of the track.

SAYAKA MITOH, YORICK POST/ELSEVIER ILLUSTRATION: KYLE SMART

MARINE BIOLOGY

'Solar-powered sea slugs' can detach their heads and grow a whole new body in weeks

The finding is an extreme example of autotomy – an animal's ability to shed part of its body when under threat

It's the sort of thing you'd expect to see in a David Cronenberg film: a species of sacoglossan sea slug is able to live as a detached head for several weeks – long enough for the severed head to grow an entirely new body and a full set of internal organs.

The discovery was made entirely by accident by researchers at Nara Women's University in Japan. A team there was studying the life cycles of sacoglossans, when PhD student Sayaka Mitoh noticed one of the heads was moving around by itself.

The head had separated from its heart and body, and immediately afterwards, it started to move about on its own, she said.

Within days, the wound at the back of the slug's head had closed up. Its heart started to regenerate within about a week. The following three weeks saw the slug regenerate a completely new body for itself.

"We were surprised to see the head moving just after autotomy," said Mitoh. "We thought that it would die soon without a heart and other important organs, but we were surprised again to find that it regenerated the whole body."

It's not yet clear how the sacoglossans accomplished this nightmarish feat, but the researchers say it might have something to do with stem cell-like cells at the severed end of the neck, which are capable of regenerating the body.

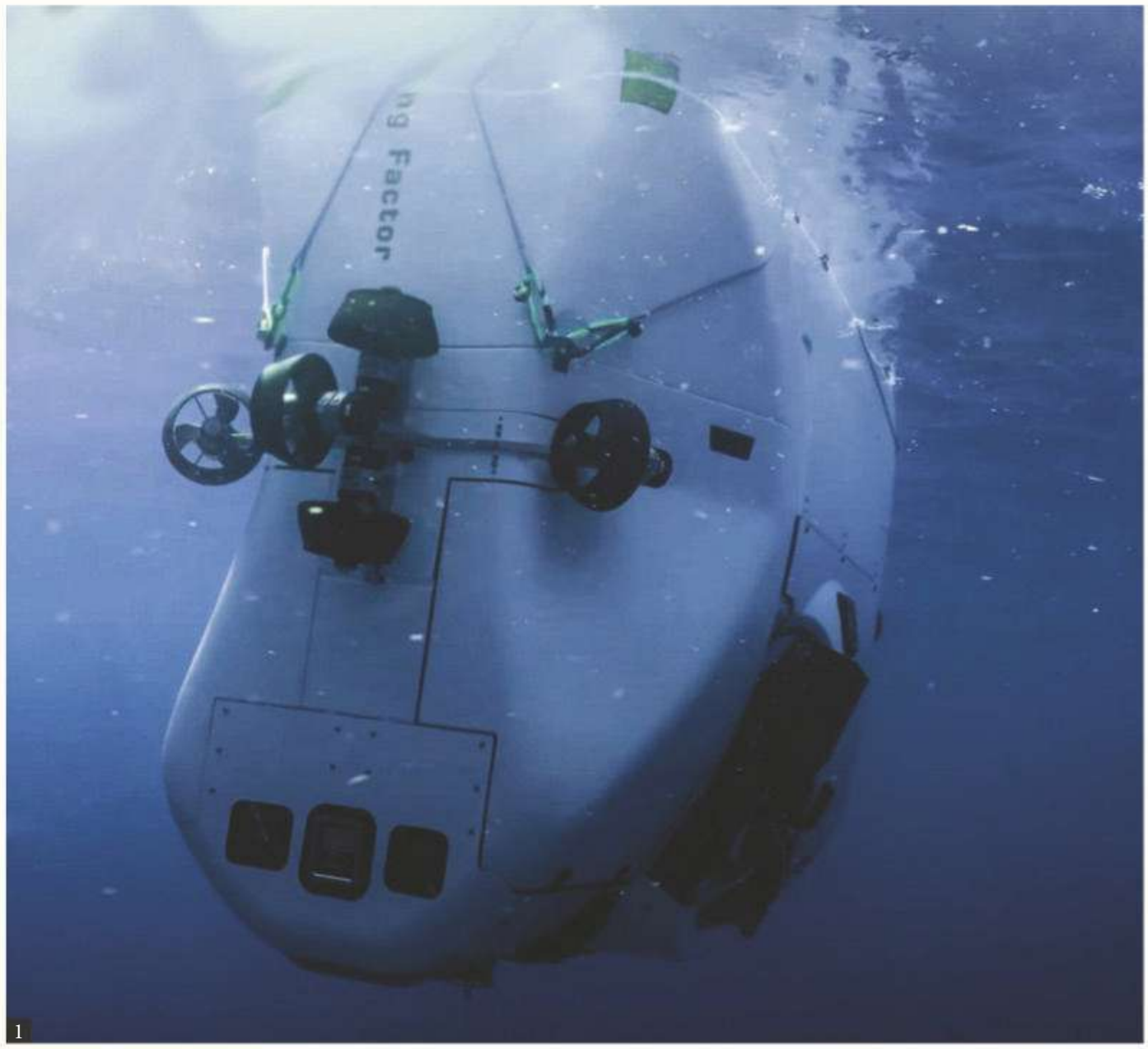
As if this wasn't strange enough already, the slugs also have another unique ability that might help them survive long enough to regenerate. They're able to incorporate chloroplasts from the algae they eat into their bodies and use them to provide energy via photosynthesis. The process, known as kleptoplasty, has led to them being nicknamed 'solar-powered sea slugs'.

The researchers are now planning new studies to further investigate the sacoglossans' bizarre behaviour.

EXPLORATION

Marathon dive to the bottom of the Mariana Trench finds new species of isopod

On Friday 5 March, Hamish Harding and Victor Vescovo were sealed into *Limiting Factor*, a two-man submersible, to begin their descent to Challenger Deep – the deepest section of the Mariana Trench, located close to 11km below the surface of the Pacific Ocean. The pair spent almost 12 hours making the round trip to the bottom and back.



1 ACTION AVIATION X6

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1. The Deep Submergence Vehicle (DSV) *Limiting Factor* begins its dive. Encased within its outer body is a near-spherical pressure hull made of 90mm thick titanium. It's one of the few manned vehicles capable of repeated dives to full ocean depth (11km).

2. Hamish Harding (left) takes a selfie sitting beside *Limiting Factor*'s pilot Victor Vescovo, as the pair descend into Challenger Deep.

3. The arm of the CLOSP lander (one of *Limiting Factor*'s three robotic support vehicles) collects unidentified isopods at a depth of 10,925m.

4. The isopods were brought back to the surface and analysed aboard *Limiting Factor*'s mothership Deep Submersible Support Vessel (DSSV) *Pressure Drop*. Early indications suggest they're a previously unknown species of the crustacean.

5. During their 12-hour dive, Harding and Vescovo spent four-and-a-quarter hours at the bottom of Challenger Deep, covering a distance of 4km along the undulating and silt-covered sea bed.

6. Hamish Harding emerges from DSV *Limiting Factor* after its safe return to the surface.

DR CARL STRATHEARN
Roboticist

Horizons

Lip-syncing robot gets one step closer to crossing the uncanny valley

The researchers used a combination of speech synthesis, machine learning and 3D-printing techniques to create a robot that accurately emulates the natural movements of the human jaw, lips and tongue

New hardware and software enables the robot to more closely replicate human mouth movements

WHAT IS THE UNCANNY VALLEY?

The uncanny valley is a point where things like humanoid robots and CGI characters start to give us an eerie feeling. And the reason for that is because they're not perfect representations of humans – they never quite get there. So, they emit these feelings of terror, unease and unfriendliness.

From birth we're able to detect and analyse faces. And faces play such an important part in our communication. When we start to see things that shouldn't be there, things that are out of place, we do get that feeling of repulsion. It's not just appearance, though, it's in functionality as well. The way robots move, say. If a robot doesn't move the way we expect it to move, that again gives that feeling of unnaturalness and uneasiness.

YOUR WORK FOCUSES ON MATCHING FACIAL MOVEMENTS TO SPEECH. WHY DOES THAT PLAY SUCH AN IMPORTANT ROLE IN THIS?

The two key areas in the uncanny valley theorem are the eyes and the mouth. When we communicate, our attention goes between the eyes and the mouth. We look at the eyes to get attention and we look at the mouth for speech reading, for understanding. And with robots particularly, anything that's outside the realm of natural lip movements can be confusing and disorienting for us, especially if you're interacting over a certain amount of time.

HOW DID THE PROJECT START?

When I was first doing this project, I was helping teach in the animation department of the previous university I was at, because it didn't quite have a robotics department. So that's where these ideas started to come together. They use programs like one called Oculus, which basically takes speech and converts it into a CGI mouth with lip positions. So, it automatically reads speech and extracts the visemes [a lip shape used to form a particular sound] for the mouth positions and I wanted to do that with the robot. So, I created a robot mouth modelled on a human mouth.

But before I did that, I looked at previous robotic mouth systems to see what was missing. And that was really important just to be able to see what the key muscles were, what muscles work together, and what can be left out of this mouth.

Obviously, it's a very small area and you're confined to what you could actually put into a robotic mouth. One of the key things I found that

> **"When the algorithm came across [a sound it was familiar with], it was able to transfigure the robot mouth system to match the positions"**
>
> DR CARL STRATHEARN

was missing was something called the buccinator muscles, which are the muscles at the corners of the mouth that are used for pursing and stretching the lips when we create vowel and consonant sounds. So, I replicated these muscles and I created a robotic mouth prototype.

WHERE DOES THE SOFTWARE PART COME IN?

I thought, "Right, the next stage is to create an application that can take these lip shapes and put them into this robotic mouth." So, we used something called a viseme chart. It's something that's used a lot for CGI in game design – basically it's a list of sounds and the matching mouth shape – and I made my robot make these shapes. For each sound – the Ahs, Rs, and Oos – I had all these robotic mouth positions. And I collected and saved them into a configuration file so I'd be able to bring them out later and use them.

The next part was creating a system that could handle speech [not just pure simple sounds]. But I wanted to do it live, so there was no room for processing time. If you use processing time, then the speech becomes unnatural as there are lots of huge pauses in the conversation. So, I created a machine-learning algorithm to take speech synthesis, which is robotic speech like you have on Siri, out of the laptop and into a microprocessor that turned that audio data back into numerical data. Part of it also went into a processing system so I could actually see the sound wave like you see in a recording studio.

CAN YOU TELL ME A BIT MORE ABOUT HOW THE SYSTEM WORKS?

I created a machine-learning algorithm that could recognise patterns in the incoming speech. That was done not by monitoring the speech itself, but the patterns in the waveform. So, you're looking at the pixel size, the length of each word and each sound, and then feeding the system a bunch of samples. That way it kind of knew what it was looking for. And when it came across [a sound it was familiar with], it was able to transfigure the robot mouth system to match to the positions that I matched on the chart. That worked surprisingly well.

The next thing was what I call the voice-patterning system, which works with syllables. Obviously, when you talk your jaw moves up and down in time with syllables. So, that was the next stage to create this patterning system, which meant if there was no sound, the mouth was shut, and the louder the sound, the wider the mouth.

HOW DID YOU GO ABOUT CHOOSING THE ROBOT'S APPEARANCE?

Well, there are actually two robots in the experiment – an older-looking one and a younger-looking one. The younger robot doesn't get as much attention because I think the older robot looks more realistic. But I produced them with the idea of one being a younger version of the other. So, you have kind of the same robot.

I wanted to compare how people interacted with an older-looking robot and a younger-looking robot. What I found is that young people preferred to interact with the younger robot and older people preferred to interact with the other older robot.

I also gave them personalities. I thought, well, I'm quite young, so I'll base the younger personality on myself. And I know my dad pretty well, he's kind of old, so I modelled the older one on him. I had the younger robot be interested in what I'm interested in and the older one be interested in snooker and John Smith's beer.

WHAT ARE THE POTENTIAL APPLICATIONS OF THIS TYPE OF WORK?

I always use Data from *Star Trek* as the perfect example for this, because he acts like this very humanistic interface between lots of different things: people and aliens – obviously aliens that don't speak English so he acts as a translator. But he also acts as the interface between the ship's computer and people. So, things that would be very difficult for humans, say calculations, he's able to translate that information and give it in a simplified way – a humanistic way, with emotion, with facial expressions. And that's what I think this technology will eventually head towards.

We have to remember that not everybody can interact with technology effectively. We're very privileged, I think, to have grown up with technology and to be able to use it. But there are lots of people in the world who don't have that, so creating something like a humanoid robot would allow them to integrate with technology a lot more naturally.

DR CARL STRATHEARN

Carl is a research fellow at the School of Computing at Edinburgh Napier University. ***Interviewed by*** **BBC Science Focus** ***commissioning editor Jason Goodyer.***

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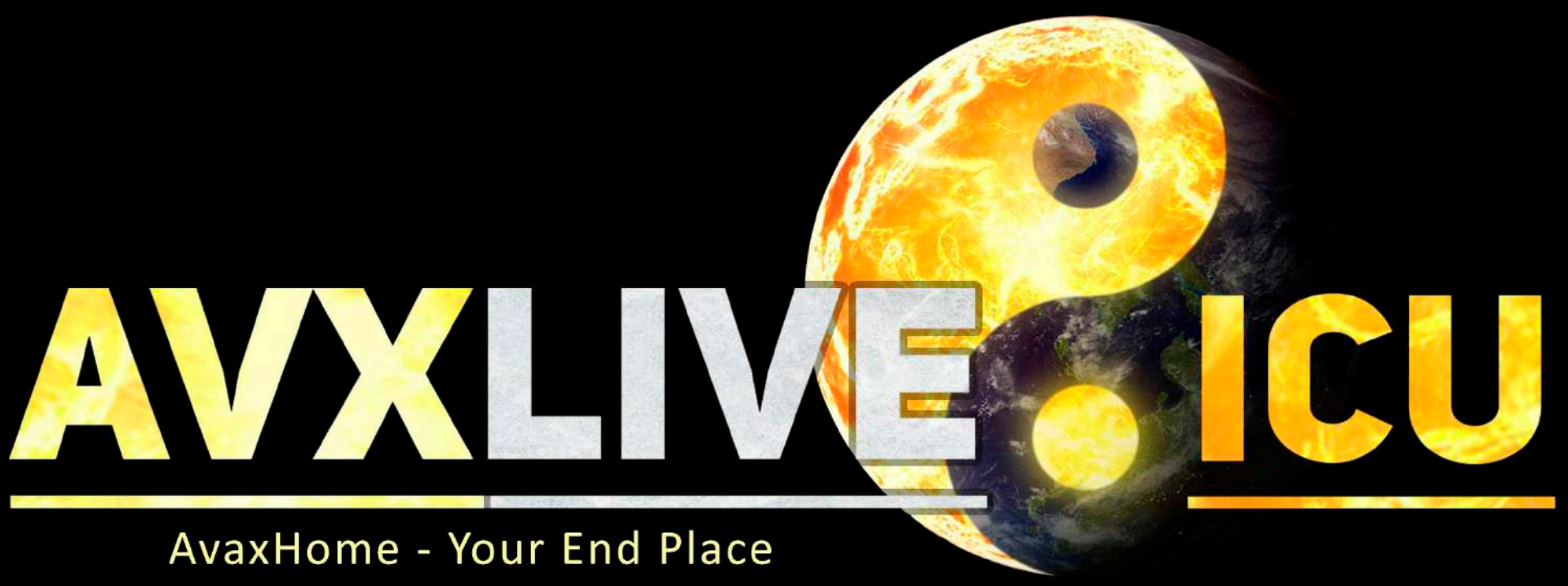

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EYE IN THE SKY

AS THE JAMES WEBB SPACE TELESCOPE READIES FOR ITS LAUNCH LATER THIS YEAR, WE TAKE A LOOK AT HOW THIS HUBBLE SUCCESSOR WILL ECLIPSE ITS PREDECESSOR

WORDS: NISHA BEERJERAZ-HOYLE
PHOTOS: NASA/GODDARD SPACE FLIGHT CENTER

Engineers pose with the JWST after it emerges from 100 days of cryogenic testing inside Chamber A at NASA's Johnson Space Center in Houston. All parts of the JWST were subjected to rounds of cryogenic testing to ensure they could withstand the extreme cold of space.

After nearly 20 years of development and 16 launch delays, the James Webb Space Telescope (JWST) is almost ready. Set to launch on 31 October 2021, the largest space observatory ever built is set to revolutionise our understanding of the cosmos and help solve some of the Universe's greatest mysteries.

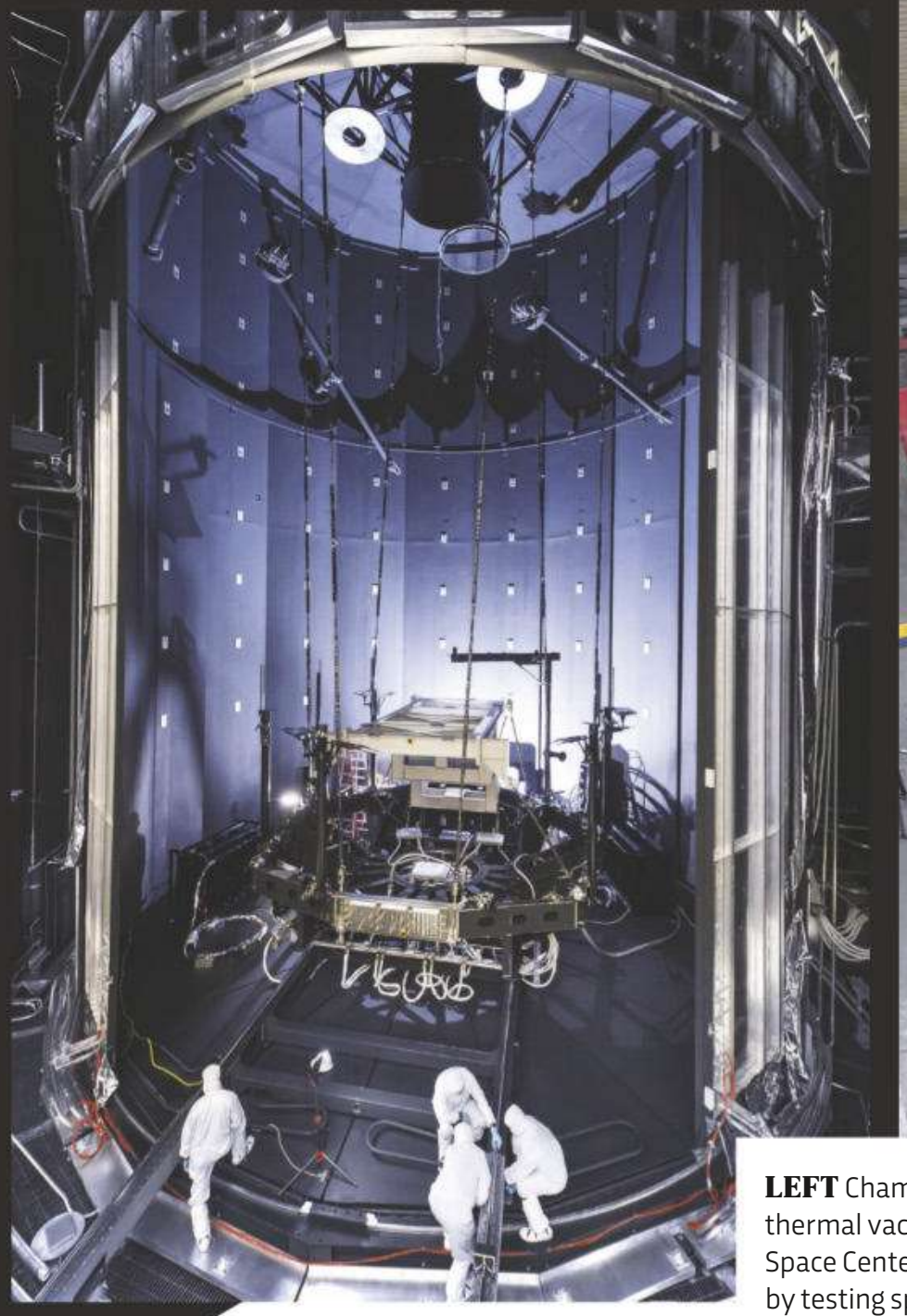
It hasn't been an easy journey. First conceived 30 years ago as the successor to the Hubble Space Telescope, the 'Next Generation Telescope' as the JWST was first known, has survived threats of cancellation, changes of leadership and numerous postponements. Expected to cost $10bn (£7.2bn approx), the JWST (named after NASA's second administrator James E Webb) is the sixth most expensive space mission of all time. And it's not surprising: the JWST is brimming with innovation and complexity, is the product of a large international collaboration between the US, European and Canadian space agencies, and is often described as one of NASA's biggest and boldest undertakings, one that will contribute unparalleled value to science and technology.

LOOKING DEEPER

For over 25 years, Hubble has graced us with beautiful images of the 13.8-billion-year-old Universe, capturing light emitted just 500 million years after the Big Bang. JWST's infrared 'eyes' will be able to peer even further into the Universe's early history, back to when the first stars and galaxies were born.

The telescope will also venture further from Earth than its predecessor. While Hubble follows a close orbit, around 550km above Earth, the JWST will float up to 1.5 million kilometres from us and orbit the Sun. It will cast its gaze on the likes of Mars, comets, dwarf planets and exoplanets, to teach us more about how planets and solar systems form.

Hubble isn't the only telescope the JWST will surpass though; it'll eclipse another great space observatory too: Spitzer (launched in 2003 and retired in early 2020). As Naomi Rowe-Gurney, a planetary scientist at the University of Leicester explains: "Data from Spitzer has shown some really unexpected behaviour happening on Uranus and we have no idea what's causing it. The only way we ➤



LEFT Chamber A, the world's largest thermal vacuum chamber at NASA's Johnson Space Center in Houston, was made famous by testing spacecraft used for the Apollo missions. It was remodelled by technicians to accommodate the JWST.

can find out is by using the JWST's power and infrared capabilities."

The JWST will also deepen our knowledge of exoplanets. "We're finding more exoplanets with the same masses as our ice giants, Uranus and Neptune. Because we don't know much about the ice giants in our Solar System, we can't understand those in other planetary systems. The JWST is definitely going to change how we view our Solar System," says Rowe-Gurney.

WEBB DESIGN

Looking at the telescope towering over engineers at NASA's Johnson Space Center in Houston, Texas, you can see why it's a game-changer. The JWST's primary mirror is a thing of beauty. Its honeycomb structure is an impressive 6.5m in diameter and made up of 18 adjustable, gold-plated beryllium segments. Compared to Hubble, the JWST has six times the light-collecting area and a much wider field of view (roughly 15 times larger). Yet, at 6,500kg, it's almost half the mass.

The light captured by the optics will be analysed by the four science instruments on board – collectively known as the Integrated Science Instrument Module (ISIM). The optical mechanisms need to be kept below -223°C to maximise the chances of detecting faint traces of infrared light. The Mid-Infrared Instrument (MIRI) requires an even lower temperature of -266°C, barely above absolute zero. To prevent the Sun's heat and light from interfering with its observations, the JWST is equipped with cryocoolers and a five-layer, tennis-court-sized sunshield.

Despite its huge size, the entire observatory must fold down to fit inside an Ariane 5 rocket's nose cone. Once deployed, the JWST will unfold itself, cool down and calibrate. Mission success hinges on flawless execution

of this sequence, one which has never before been attempted in space.

To add even more jeopardy, the JWST will be beyond the reach of manned repair missions, unlike Hubble, which needed five. This is why testing has been of the highest importance for the mission team every step of the way.

But, according to Paul Geithner, JWST's technical deputy project manager, assessing an observatory designed to deploy and operate in space is no easy feat. "We could not test the entire observatory as one complete entity in a simulated space environment – it's a departure from the early days of the space age when you could put an entire spacecraft into a thermal vacuum chamber and test it all at once," he explains. Instead, individual units, built in different parts of the world, were tested before they were brought together and assembled into two 'super-halves', comprising the Optical Telescope element/Integrated Science instrument module (OTIS), and the combined spacecraft bus and sunshield. Each unit was tested in acoustic and vibration chambers that replicated a violent, noisy launch, and also placed into a large freezer, known as 'Chamber A', for months to check they could withstand the freezing temperatures of space.

ABOVE The JWST's sunshield is the largest part of the observatory. The five layers of thin membrane must unfold precisely to provide a thermally stable environment. Here, engineers test a full-sized replica in a clean room at the Northrop Grumman facility in California.

The JWST's 18-segment primary mirror hangs in the clean room at NASA Goddard Space Flight Center. Six of the segments (three on either side) will fold back so the mirror can be stowed in the Ariane 5 rocket upon which the observatory will be launched.

LEFT Small dust particles can greatly affect the science the JWST is able to do, so pristine mirrors are critical. Here engineers practise using carbon dioxide snow to clean a test mirror segment and remove contaminate particulates without scratching the surface.

BELOW LEFT Mirror segments are inspected with torches for any imperfections. They're made from a light material called beryllium, which has been ground and polished, before being coated with a layer of gold only nanometres thick to optimise their infrared reflectivity.

"CUTTING-EDGE ENGINEERING OF NEW SPACEFLIGHT HARDWARE IS A HUMBLING BUSINESS"

There have been some bumps on this long road, such as loose fastening screws found after acoustic and vibration testing in 2016, and, most notably, the sunshield ripping after a test deployment in March 2018. "Cutting-edge engineering of new spaceflight hardware is a humbling business," Geithner reflects.

THE FINAL COUNTDOWN

In August 2019, the two super-halves were combined at a Northrop Grumman facility in California to undergo full integration testing. And in 2020, during the COVID-19 pandemic, the fully assembled JWST accomplished an astounding feat: it passed every single test.

Granted, prior to the testing success the JWST's launch was postponed once again. But this time it was only from March to October 2021 – a reasonable delay considering the team has had to work remotely and in socially distanced shifts, during a critical phase.

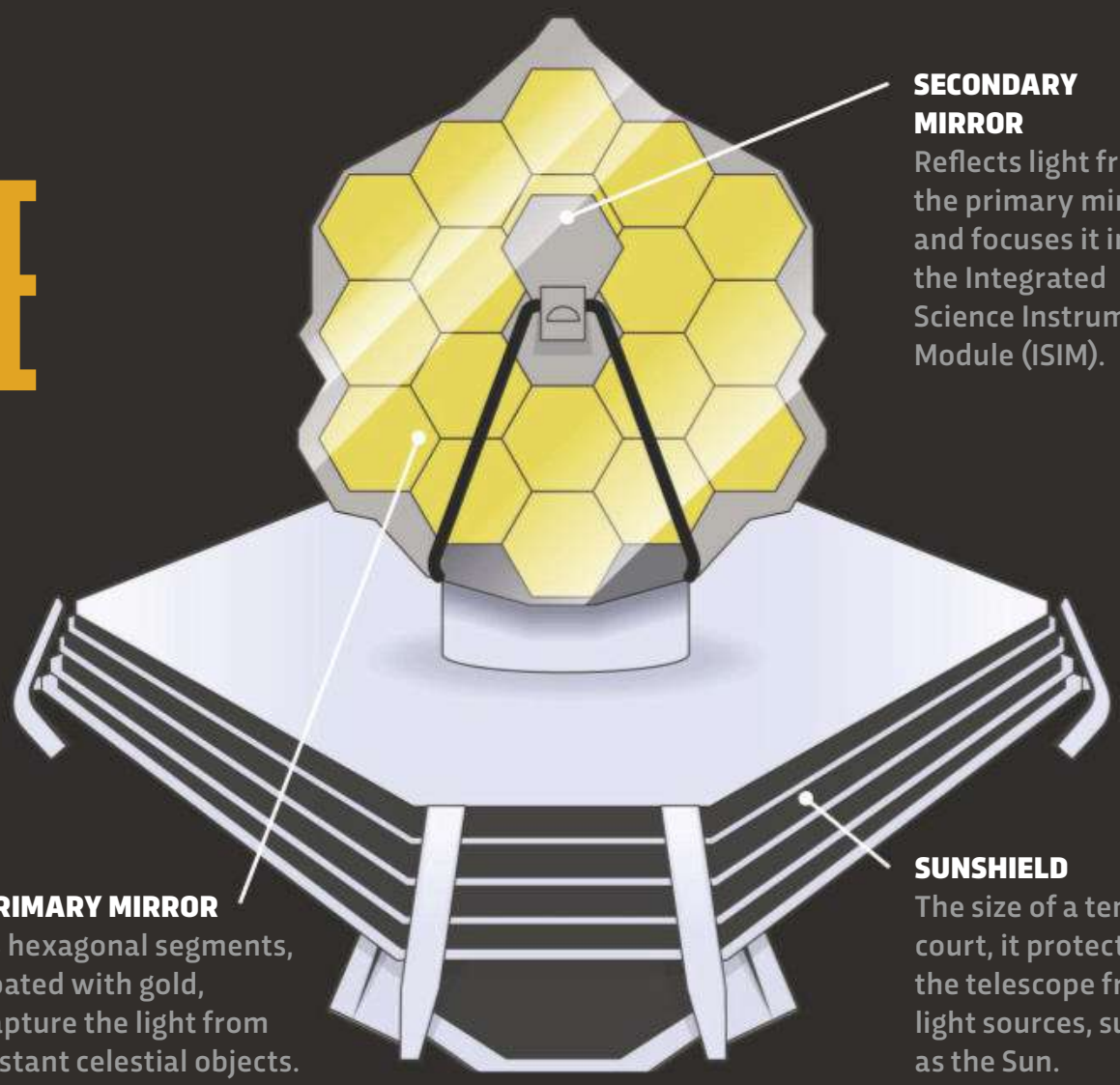
With only months left until the JWST launches from French Guiana, Geithner now has time to reflect on the power of the project so far: "While the JWST is to be a tool of science and has been a daunting engineering challenge, it is, in the end, a human story, a generational project." Indeed, there is no doubt the discoveries it could make will serve generations to come. **SF**

by **NISHA BEERJERAZ-HOYLE**

Nisha is a freelance space and astronomy writer.

THE TELESCOPE IN FOCUS

THE JAMES WEBB SPACE TELESCOPE WILL IMAGE THE LITTLE KNOWN PLACES IN THE MILKY WAY AND BEYOND. HERE ARE JUST A FEW OF THE THINGS IT HOPES TO SEE AND THE TECH IT WILL USE TO SEE THEM...



SECONDARY MIRROR
Reflects light from the primary mirror and focuses it into the Integrated Science Instrument Module (ISIM).

PRIMARY MIRROR
18 hexagonal segments, coated with gold, capture the light from distant celestial objects.

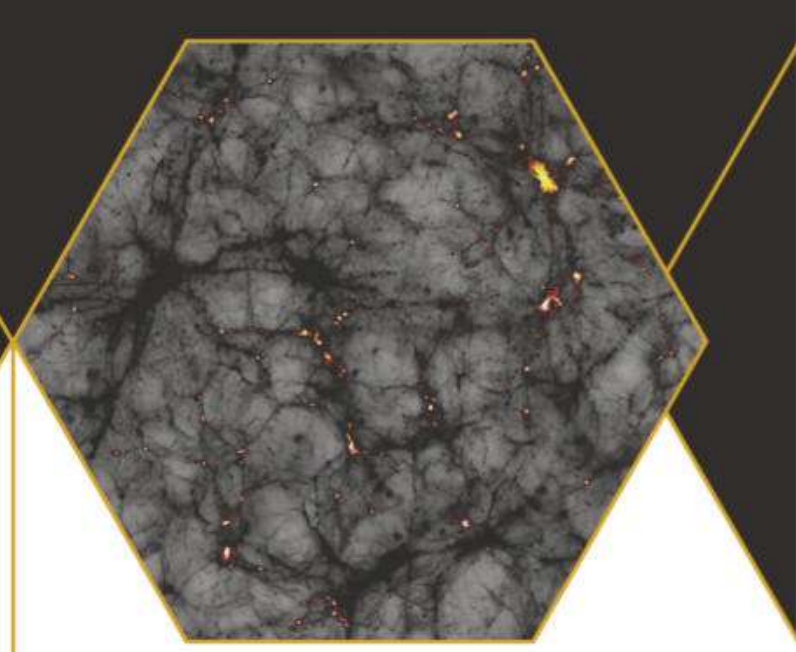
SUNSHIELD
The size of a tennis court, it protects the telescope from light sources, such as the Sun.

FIRST LIGHT

The JWST will be able to look back to around 200 million years after the Big Bang, when the first stars in the Universe formed. The first stars are thought to have been massive giants made of hydrogen and helium, whose short lives ended in the supernovae that created the heavier elements we detect in younger stars today. To see this period in cosmic history, we need sensitive infrared instruments to detect the faint traces of light that have travelled through space and time to reach us.

ANCIENT GALAXIES

The JWST will also look back to the very first galaxies in the Universe to learn more about their evolution and why there's so much variety in them. Nearly all the spiral and elliptical galaxies that we see today have experienced at least one collision or merger with another local galaxy. Yet older galaxies look entirely different to their modern counterparts – smaller, clumpier, less structured. Examining galaxies can also inform us of the macrostructure of the Universe and how it's organised on a large scale.



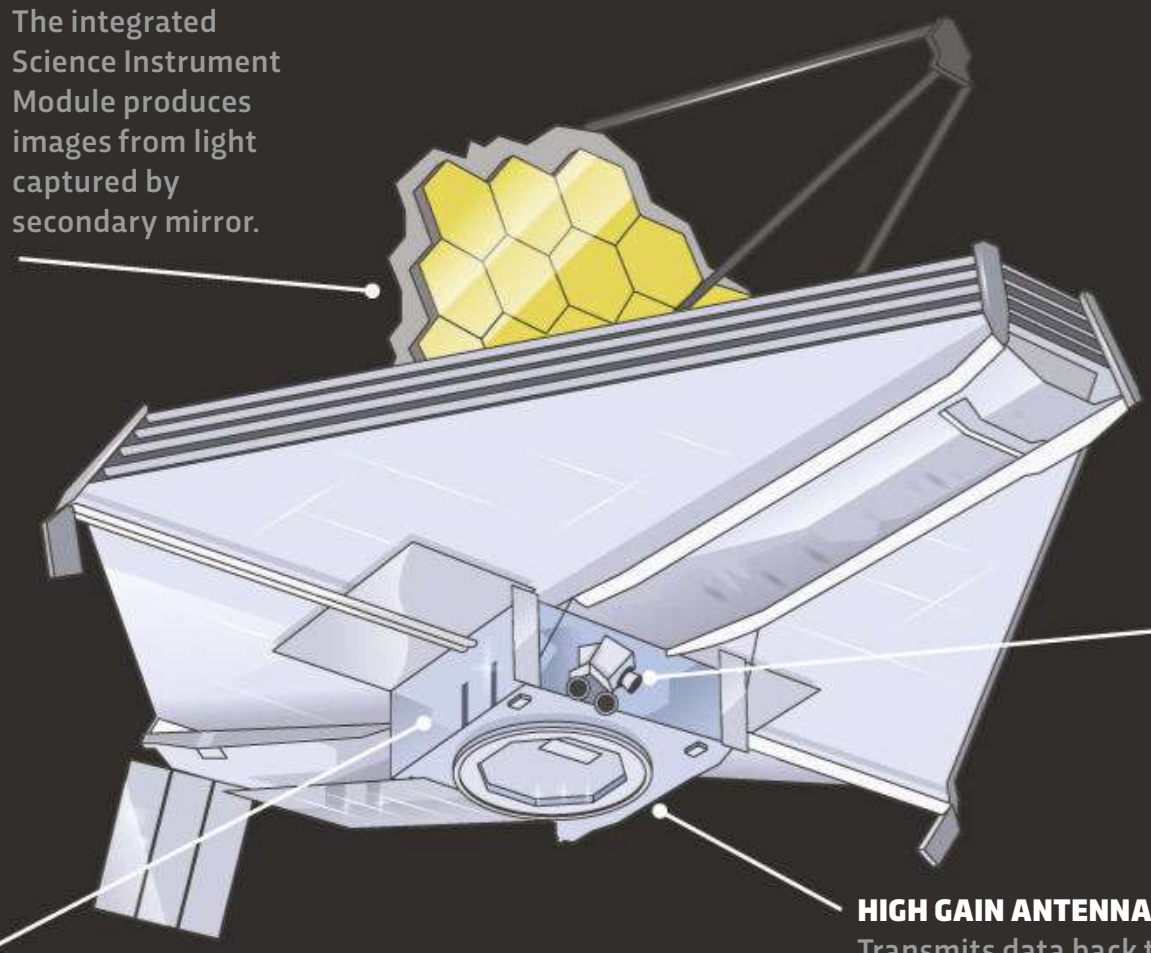
DARK MATTER

Dark matter is thought to play an important role in the structure of the Universe, accounting for five times the mass of normal, baryonic matter such as atoms and particles. Considered to be the scaffolding for the Universe, we're only able to observe dark matter indirectly by measuring how its gravity affects stars and galaxies. The JWST won't be able to see dark matter, but it will employ gravitational lensing techniques to study the most distant galaxies and look at their rotation for signs that dark matter is at play.

NASA, D BERRY/NRAO, GETTY IMAGES X3 ILLUSTRATION: ACUTE GRAPHICS

JWST FACT FILE

SIZE: 21 x 14m (sunshield)
LAUNCH MASS: 6,200kg
COST TO BUILD: $10bn
LAUNCH DATE: 31 October 2021
EXPECTED FIRST IMAGES: 2-3 months after launch
COLLABORATORS: NASA, ESA and Canadian Space Agency
MISSION DURATION: 5-10 years
ORBIT: 1.5 million km from Earth

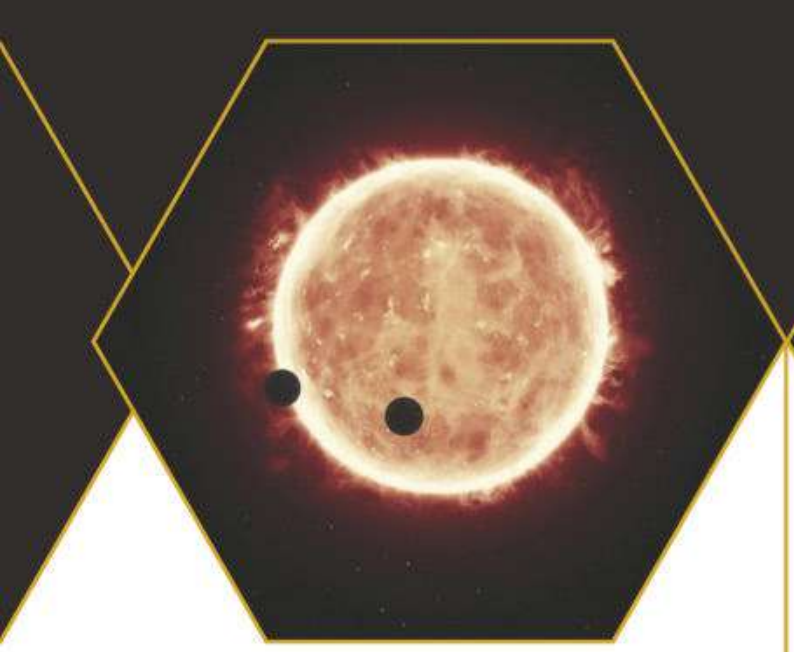


ISIM
The integrated Science Instrument Module produces images from light captured by secondary mirror.

STAR TRACKERS
Small telescopes that observe star patterns to help aim the telescope.

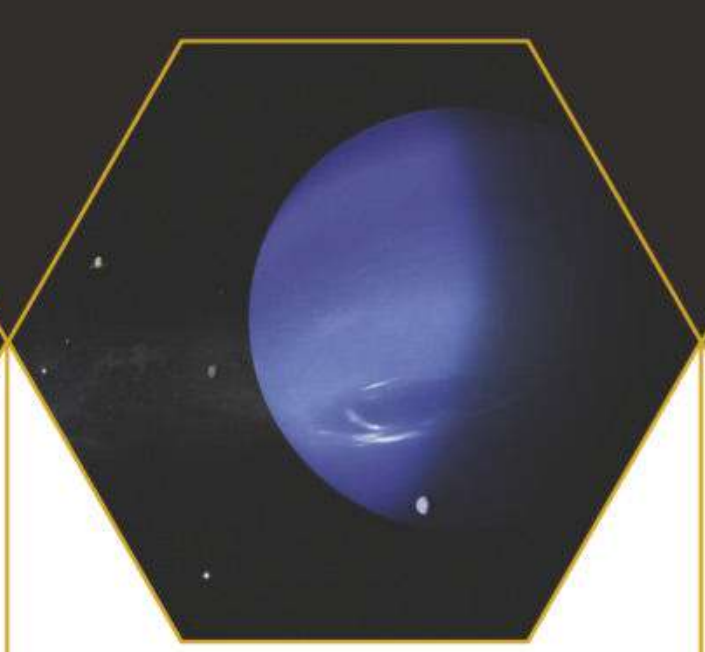
HIGH GAIN ANTENNA
Transmits data back to Earth and receives commands from NASA's Deep Space Network.

SPACECRAFT BUS
Contains most of the steering and control machinery.



EXOPLANET ATMOSPHERES

The JWST will help answer the big question of whether life exists beyond Earth by studying a variety of exoplanets – planets outside our Solar System. Of particular interest is the TRAPPIST-1 system, where three of its seven planets are in the habitable zone and one may harbour liquid water. The JWST will observe the planet as light from its parent star passes through the planet's atmosphere, revealing its chemical composition and the gases that are present there.



OUR ICE GIANTS

While the JWST's primary science aims lie more in cosmology and star formation, it'll also take a closer look at a couple of familiar objects – our ice giants, Neptune and Uranus. The JWST will map their atmospheric temperatures and chemical composition to see how different they are – not only to each other, but also their gas giant cousins, Jupiter and Saturn. The ice giants are at least 30 times further from the Sun than Earth and are the least understood planets in our Solar System.

PLUTO AND THE KBOs

Dwarf planet Pluto and its fellow Kuiper Belt Objects will also be receiving some observation time. The JWST is powerful enough to study such icy bodies including comets, which are often-pristine leftovers from our Solar System's days of planet formation and could hold clues to Earth's origins. There are no planned missions dedicated to the outer Solar System for years, so new observations and data will play a big part in planning for future planetary missions.

RISING OUT

DESTINATION

3,112m
BELOW SEA LEVEL
CENTRAL PACIFIC

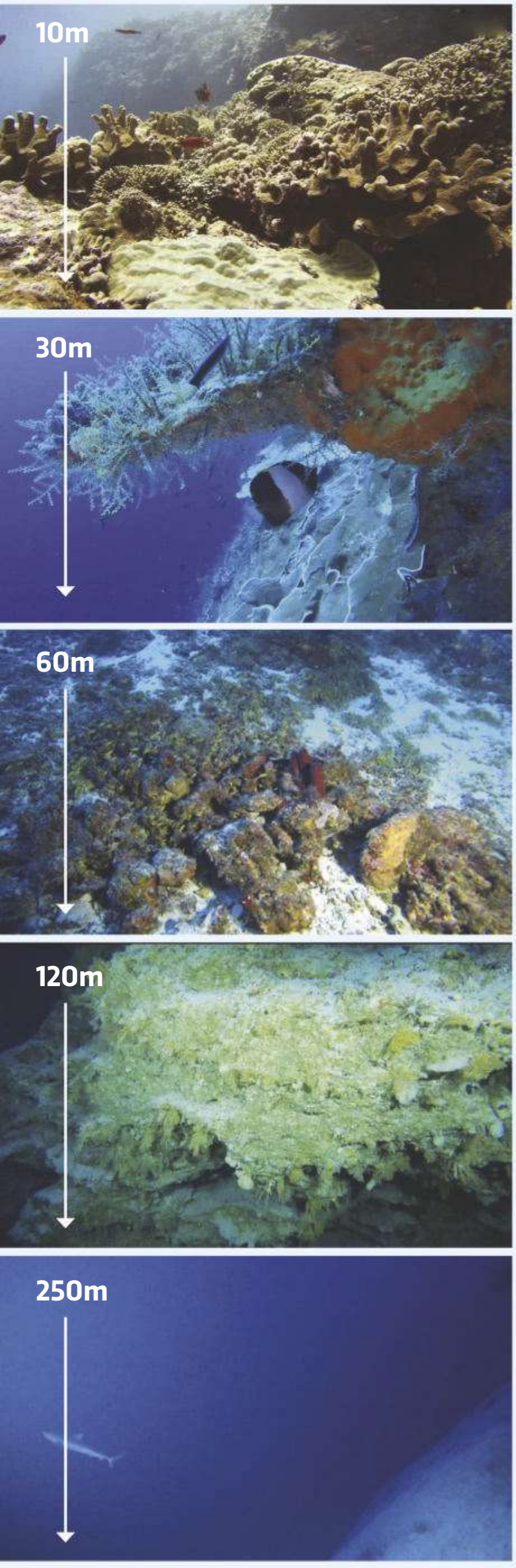
NEKTON

OF THE ABYSS

Scientists descend into waters off the Seychelles in 2019 to glimpse the peaks of the seamounts hidden in the depths

On land, the highest mountains reach up to the sky and their slopes are blanketed with cloud. In the ocean, the tallest peaks stretch towards the surface and their sides are swathed in plankton. Let's explore the hidden world of seamounts...

by DR HELEN SCALES



On land, you'd struggle to find a mountain that hasn't already been climbed. In contrast, in the deep sea there are thousands of unexplored peaks. Seamounts are submerged volcanoes, active or dormant, with foothills planted in the abyss and summits soaring up thousands of metres without breaking the sea surface. These hidden mountains are some of the least known, but most abundant geological features on the planet. They form a fragmented habitat that covers an area rivalling the world's tropical rainforests. As scientists learn more about seamounts, it's becoming clear that these dramatic montane seascapes are rich oases of life that play a crucial role across the entire global ocean.

ENORMOUS, ABUNDANT AND UNEXPLORED

Currently, there's no definitive count of the world's seamounts, because locating and identifying them is not easy. Estimates suggest there are between 30,000 and more than 100,000 seamounts with peaks over 1,500m high. One of the biggest is Davidson Seamount off the California coast – 42km long, 8km wide and 2,280m tall. Taller still are seamounts that rise almost 5,000m from base to peak. Add in smaller peaks, 100m and higher, and the estimated global tally reaches into the millions.

> **"Estimates suggest there are between 30,000 and more than 100,000 seamounts with peaks over 1,500m high"**

Whatever the number of seamounts, scientists have studied only a few hundred. Dr Lucy Woodall is a senior research fellow at Oxford University and principal scientist at the research foundation Nekton, who has studied seamounts in the Atlantic, Indian and Southern Oceans. "It's something I think about before every dive, that I'm probably the first human to see this bit of our planet, just because they're so remote and so unexplored," she says.

When exploring seamounts, scientists often encounter otherworldly forests of sponges and corals, including colourful, shrub-like colonies of gold and black corals that live for hundreds or even thousands of years. Deep-dwelling coral species already outnumber their distant relatives in the tropical shallows and new species are constantly being found. A recent expedition to the Galapagos Marine Reserve uncovered dozens of new species of corals and sponges growing on three previously unexplored seamounts.

Amid the expanses of mud-covered deep-sea floor, the rocky flanks of seamounts provide a footing for larvae of corals and sponges to settle on and grow. The corals and sponges then offer a habitat for other animals: starfish, anemones, snails, brittlestars,

LEFT A 2019 Nekton expedition caught these images while descending a seamount near the Astove Atoll, in the Seychelles

NEKTON, ALAMY, DEEP SEA FISH ECOLOGY LAB/ASTRID LEITNER/JEFF DRAZON/SOEST/DEEPCCZ EXPEDITION

shrimp, squat lobsters and octopuses. Sharks lay their egg cases among the coral branches like Christmas tree decorations.

REMOTE TECH

The dives Woodall and other seamount explorers undertake are often conducted from afar, using Remote Operated Underwater Vehicles, or ROVs. These deep-diving robots, roughly the size of a car, are deployed from a ship and controlled via cable. Equipped with high-definition cameras and robotic grippers, they become the scientists' eyes and hands in the deep. Seamount surveys are usually conducted from the base to the summit, along pre-determined transect lines, filming and photographing bands of habitat that can be scrutinised in detail later.

As well as surveying habitats and searching for new species, scientists also visit seamounts to hunt for novel molecules that could inspire new medicines. Deep-sea corals and sponges are proving to be especially useful because they produce a huge range of chemical defences. Scientists get samples of tissue from the corals and sponges, then isolate and analyse the molecules produced by the animals and the microbes that live inside them. The samples are yielding all sorts of complex, toxic molecules that are showing great promise as new antibiotics, as well as treatments for cancers and pathogens such as tuberculosis and malaria.

Long-lived corals also keep a record of how the ocean has changed. By extracting traces of certain chemicals and measuring isotopes, scientists can estimate the temperature, pH and nutrients of seawater when different parts of the coral colony grew, some more than 4,000 years ago.

THE SEAMOUNT EFFECT

The least-known seamounts are those lying deepest underwater and yet, as deep-sea biologist Dr Astrid Leitner from the Monterey Bay Aquarium Research Institute points out, "those are actually the most common types of seamount on our planet". In 2018, while she was a PhD student at the University of Hawai'i at Manoa, Leitner took part in a seamount-finding expedition to the central Pacific and made a remarkable discovery: an ultra-deep, abyssal seamount, peaking 3,112m below the surface. Leitner and the team deployed a baited camera to study the apex predators – chiefly fish – that hunt around it and won't pass up a free meal dropped down by scientists.

When the camera was brought to the surface 24 hours later, Leitner thought it had malfunctioned. Thumbnail images on her computer appeared to be black. Playing the footage in full she realised it was a swarm of half-metre-long fish, called cutthroat eels. "We were absolutely shocked," she says. In one shot she counted 115 eels, an unheard abundance for any fish in the abyss where food is in short supply and predators are normally rare. "Compare that to what we've seen across the deep sea and it blew everything else out of the water."

Leitner set baited cameras on other deep seamounts and found more eel aggregations, but saw none in the surrounding ➲

TOP A scuba diver peers down into El Bajón, a volcanic seamount in Spain's Mar De Las Calmas marine reserve

ABOVE Cutthroat eels swarm a bait package at an unnamed seamount more than 3,000m below the surface of the Pacific

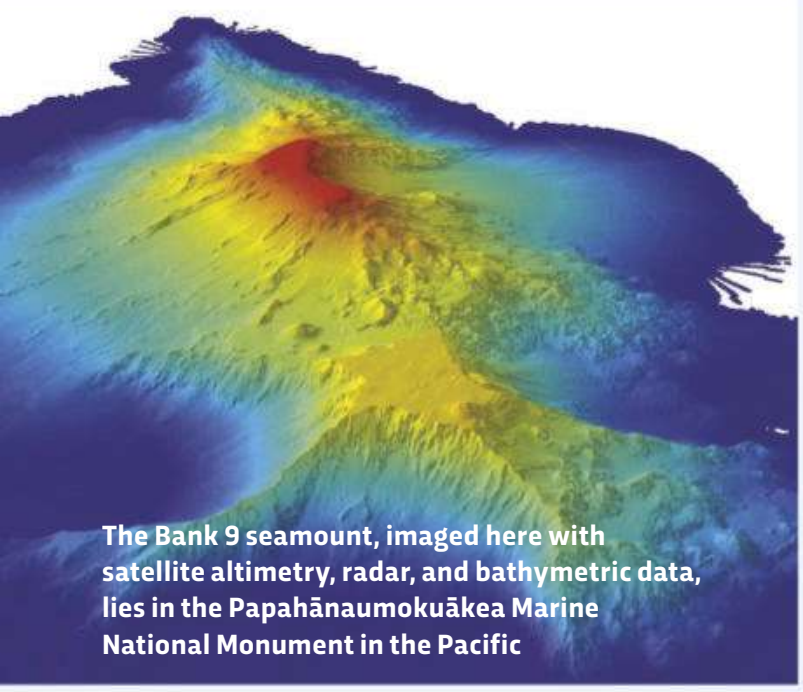
RIGHT Brittlestars feed among the branches of coral on the Dickins Seamount in the Gulf of Alaska

SEARCHING FOR SEAMOUNTS

The biggest seamounts, 1,500m and taller, can be spotted from space, even though their peaks don't show above the surface. Satellites measure slight bulges in the sea surface, caused by the gravitational pull of massive, basaltic mounts that draw seawater in and pile it up above them. Newer satellite sensors capable of spotting smaller peaks, 1,000m and taller, will soon add to the global count of seamounts.

To find smaller and deeper seamounts – and to build accurate 3D maps – requires multi-beam sonar devices that scan the seabed using sound. These are either ship-based or are fixed to deep-diving, autonomous robots. "It's a really interesting process," says Dr Astrid Leitner, who has searched for ultra-deep seamounts in the central Pacific. "You're multi-beaming, then you have to clean up the data and you're seeing the shape of the seafloor evolving as you're going."

Arguments abound as to whether less imposing peaks fall within the definition of seamounts. Even on land there's no agreed height above which a hill becomes a mountain. In the ocean, there's no clear geological or ecological distinction between large and smaller seamounts, although a commonly accepted cut-off is 1,000m.



The Bank 9 seamount, imaged here with satellite altimetry, radar, and bathymetric data, lies in the Papahānaumokuākea Marine National Monument in the Pacific

areas, suggesting they're seamount specialists and providing evidence that the so-called 'seamount effect' extends into the abyss. Seamounts are magnets for sea life, although exactly why is something deep-sea biologists are still trying to explain.

One theory is based on the way that currents that flow over abyssal plains speed up when they meet a seamount and are forced around it. Faster currents bring in a constant stream of suspended particles and plankton, on which filter-feeding animals gorge. This injection of food then works its way up the food chain and could ultimately support high densities of predators, such as cutthroat eels. "We don't have much evidence for that yet," admits Leitner. "That's one of the guesses we have."

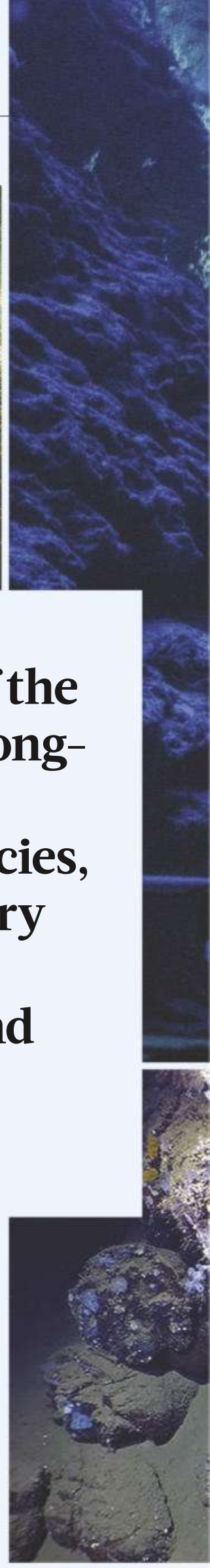
> **"The basis of the habitat are long-lived, slow-growing species, so they're very quick to be destroyed and very slow to come back"**

FISH FINDING

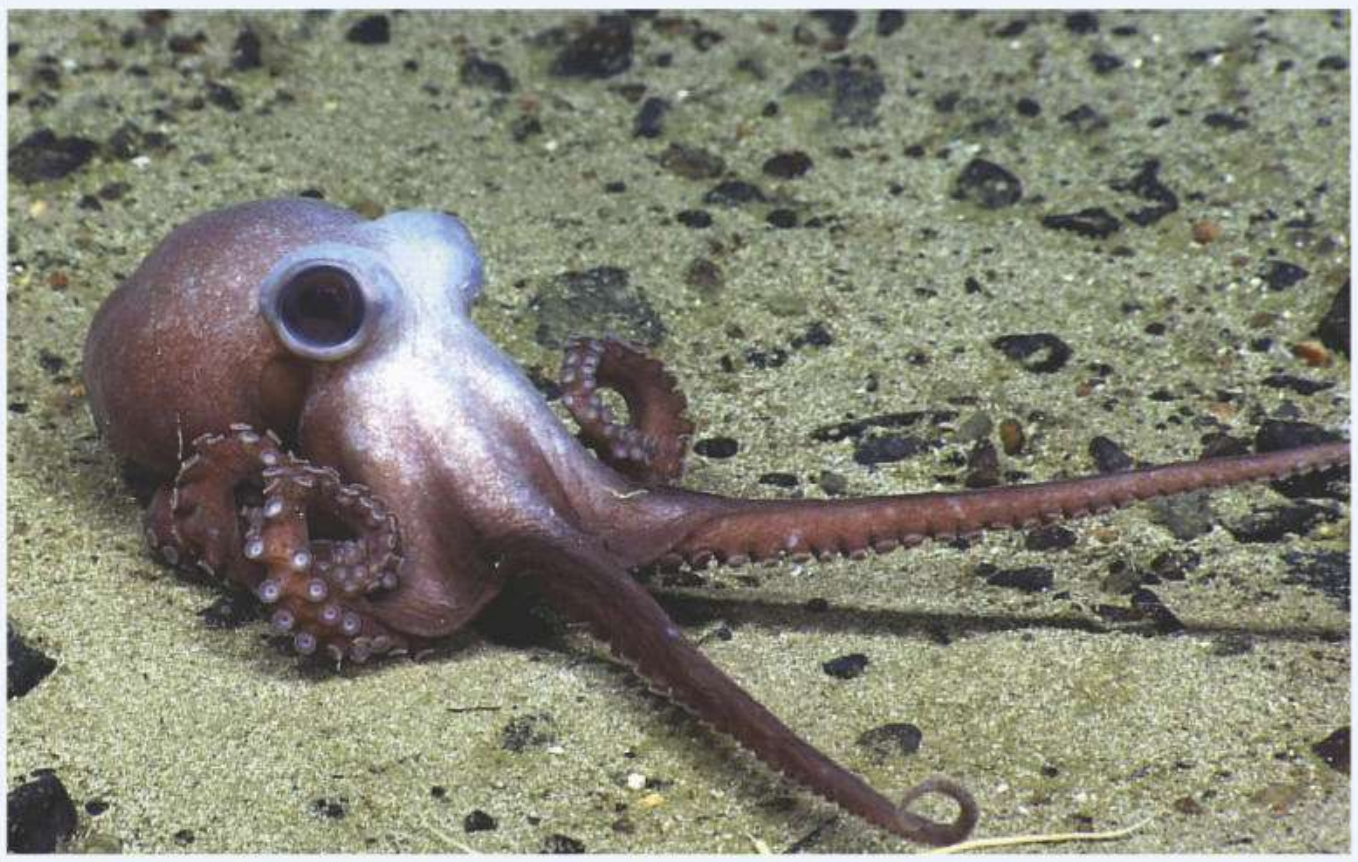
While scientists are still investigating what causes the seamount effect, fishing industries have been taking advantage of it for decades. On shallower seamounts, ones within a few hundred metres of the surface, trawlers have targeted aggregations of fish including species that come to seamounts to spawn.

In the 1990s, orange roughy fisheries boomed on seamounts worldwide, but swiftly collapsed as trawl nets smashed their way through ancient coral ecosystems. "Trawl fishing leaves horrendous scars on these seamounts," says Leitner. Decades after the trawlers move on, many seamounts still show few signs of the delicate ecosystem recovering. "The basis of the habitat are long-lived, slow-growing species," she says, "so they're very quick to be destroyed and very slow to come back."

Seamounts and their ecosystems are gradually gaining protection from trawling, such as those within the Papahānaumokuākea Marine National Monument, which former US president Barack



NOAA/OCEAN EXPLORATION X2, ALAMY, NEKTON, ADAM SOULE/WHOI



ABOVE A young octopus stretches out on the Physalia Seamount off the northeast coast of America

ABOVE LEFT A Nekton submersible inspects a seamount in the Seychelles during the 2019 expedition

LEFT Corals and other marine life sit 700m below the surface on a seamount off the southern coast of Fernandina Island in the Galapagos

by **DR HELEN SCALES** *(@helenscales)*
Helen is a marine biologist, writer and broadcaster. She teaches at Cambridge University and her latest book, The Brilliant Abyss *(£16.99, Bloomsbury Sigma), is out now.*

Obama expanded in 2016 to encompass 1.5 million km² of the Pacific around the northwestern Hawaiian Islands. Negotiations are underway at the United Nations for a new global ocean treaty that could make it easier to protect seamounts in the high seas, those remote reaches of the ocean that no countries claim.

Protection benefits not only the resident fish and the sponge and coral ecosystems, but multitudes of migrating animals that call in at seamounts. "You get sharks, tuna, marine mammals, turtles and seabirds that know where these features are," says Leitner. Some may use seamounts as navigational tools, many come to feed. Humpback whales pause at seamounts on their seasonal migrations, perhaps using them as a sonic arena to help reflect and broadcast their songs through the ocean.

FILLING THE GAPS

Even among the shallower seamounts that reach closer to the surface there's still much to learn, especially in regions where few scientists have visited. "At the moment, there's a bias in what we understand about seamounts," says Woodall.

The best known are in the Atlantic and Pacific, within reach of major centres for deep-sea research in Europe, North America, New Zealand and Japan. Woodall and the Nekton team hope to go on an expedition to the Indian Ocean in 2022 to explore some of the lesser-known mounts. "We know very little about tropical seamounts," she says. "We know almost nothing about the biology of seamounts in the area to the north of Seychelles."

Collaborating with research partners from nations of the Western Indian Ocean, the Nekton team will explore seamounts thought to form important habitats for the migrating tuna that underpin regional economies. Woodall plans to work with scientists from across the Indian Ocean and identify research questions important for people in the region. "As part of the plan, we'll use an array of equipment including highly novel, low-cost options so that, together, we can remove some of the historical barriers to conducting deep-sea science," she says. With more eyes on seamounts, scientists will be able to increasingly join these vital dots across the ocean. **SF**

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INSIDE THE GREAT PYRAMID OF GIZA

Muons, produced by the cosmic rays constantly bombarding Earth's atmosphere, are able to penetrate the dense stone walls of Egypt's pyramids

INSIDE INFORMATION

Muon tomography is a non-invasive investigation technique made possible by particles travelling through space at almost the speed of light. And it's revealing secrets buried deep inside ancient pyramids and volcanoes

WORDS **ROBERT BANINO**

By 13 October 2016 Mehdi Tayoubi already knew his ScanPyramids project was on the right track. That was the day Tayoubi and his team met with a committee of Egyptologists to tell them about the small, previously unknown cavity they'd found in the north face of the Pyramid of Khufu, also known as the Great Pyramid of Giza. The ScanPyramids project had begun just 12 months earlier, but was already yielding promising results.

Then later, in 2017, it struck gold: a huge void was detected deep within the 4,500-year-old pyramid. Although the void's precise orientation was unknown, Tayoubi's team was able to confirm that it was about 30 metres long and situated above the Grand Gallery – the corridor linking the Queen's chamber to the chamber containing Pharaoh Khufu's sarcophagus. It was the first major new structure discovered in the pyramid since the 19th Century.

"We don't know whether this big void is horizontal or inclined. We don't know if this void is made by one structure or several successive structures. What we are sure about is that this big void is there, that it is impressive, and that it was not expected – as far as I know – by any sort of theory," said Tayoubi when the news broke in November 2017.

But perhaps more impressive than the two discoveries was the fact that they'd been made while the pyramid remained perfectly intact. There had been new no excavation or disassembly of the structure. No chamber walls were drilled through and no sealed corridors opened up. The ScanPyramids team had peered deep into the limestone blocks stacked up to form the walls of the 140-metre-high tomb and identified hollows within them that nobody knew existed. And what made this astonishing feat possible was a technique known as muon tomography, which allows scientists to explore locations that have previously been out of reach.

"It was the first major new structure discovered in the pyramid since the 19th Century"

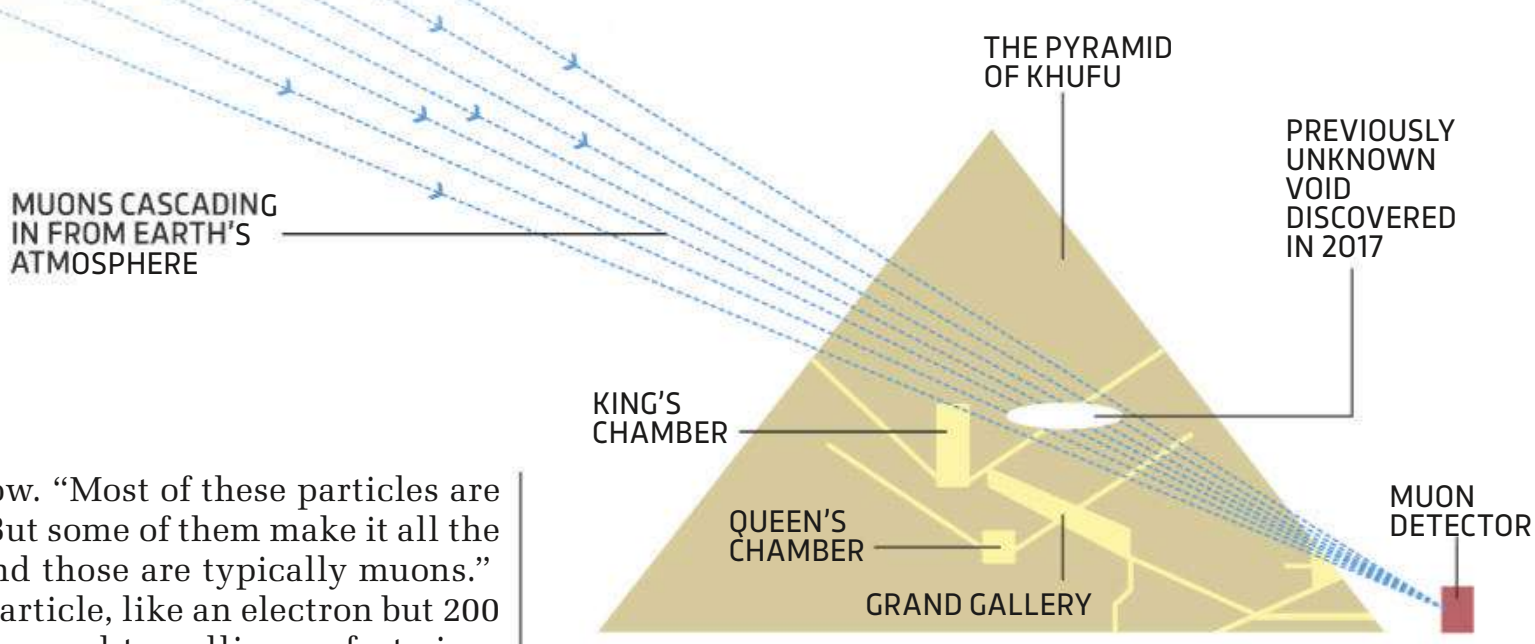
IT CAME FROM OUTER SPACE...

Muon tomography is a little like space exploration in reverse. Instead of using instruments constructed on Earth to investigate space, it relies on cosmic rays produced in space to delve into things on Earth.

Cosmic rays are high-energy particles that hurtle through space at near the speed of light. They're produced by the Sun, supernovae events outside the Solar System and even the Big Bang. They're travelling in every direction all the time and there are so many of them that they're constantly colliding with the oxygen and nitrogen molecules in Earth's atmosphere. At which point, they set off a cascade of other particles, much like a white ball breaking the pack of reds in a game of snooker.

"[When] a high-energy cosmic particle hits the upper atmosphere, it produces a large shower of particles," explains Prof Ralf Kaiser, a physicist

ILLUSTRATION: ANDY POTTS, GETTY IMAGES



at the University of Glasgow. "Most of these particles are stopped in the atmosphere. But some of them make it all the way down to the ground. And those are typically muons."

A muon is an elementary particle, like an electron but 200 times heavier. Being so heavy and travelling so fast gives them a greater ability to penetrate dense material than other types of radiation, such as X-rays or gamma rays. But unlike X-rays and gamma rays, cosmic ray muons don't damage the material they pass through.

"[Muons can] cross tens of metres of concrete. They'll also pass through your body without doing anything," says Kaiser. "They're ubiquitous, penetrating and cost-free. They're everywhere and they're part of the natural environment."

In short, muons are just the thing for getting a glimpse inside structures you can't get into, structures like sealed chambers in pyramids, closed-off caverns in archaeological sites and conduits inside volcanoes. The trick to doing that however, is catching the muons that have passed through the structure and using them to create an image of what's inside.

LOOKING FOR SHADOWS

Dr Giovanni Macedonio, the principal investigator of the MUon RAdiography of VESuvius (MURAVES) project, likens the process to getting an X-ray. When there's an object, let's say your arm, between the source of the X-rays and the camera, your arm absorbs some of the X-rays passing through it. The different densities of the skin, muscles, blood vessels and bones determine how many of the X-rays reach the camera – the denser those things are, the more X-rays they absorb.

"[Essentially,] we see the shadows of the different parts," says Macedonio. The lighter the shadows, the denser the part and, armed with that knowledge, it is possible to distinguish between the parts inside. The same principle applies to muon tomography and the objects, such as Mount Vesuvius, it's used to investigate.

"Instead of X-rays, we have muons," says Macedonio. "Muons are coming from all directions around Earth, but we're interested in the ones that are travelling close to horizontally, so they can penetrate the volcano. The muons that pass all the way through Vesuvius produce a shadow behind it." By placing muon detectors nearby, Macedonio and his colleagues can generate an image of that shadow, study the densities of the materials depicted in it and begin to distinguish the structures inside Vesuvius.

But studying something as big as a volcano requires patience, because muons are tiny and only about 100 of them hit any given square metre per second. So although they may be constantly bombarding Earth, collecting enough of them to provide useful information on something the size of Vesuvius takes a while.

"The flux of muons is not strong," says Macedonio. "Most of them are absorbed by the volcano so we do need a lot of time – we need months."

So when you do eventually get a picture, what can you do with it? Can you use it to predict eruptions? No, not exactly. But what you can do is understand the relationship between the geometry of the volcanic conduits and the style of eruptions. In particular, what conditions may cause ash clouds (that can ground planes and collapse roofs) or pyroclastic flows (fast-moving, super-heated mixes of rock fragments and gases capable of burning anything in their path) if Vesuvius were to erupt. And if you combine this information with seismic and meteorological data, you can alert or evacuate anyone who might be in harm's way when an eruption is due.

MUON DETECTION

Muons, produced by cosmic rays hitting molecules in the atmosphere, cascade to Earth, penetrating structures in their path. Those that aren't absorbed by the structures can be detected by instruments positioned within or near the structures they pass through.

"Being so heavy and travelling so fast gives muons a greater ability to penetrate dense material than other types of radiation"

THE RIGHT PLACES TO LOOK

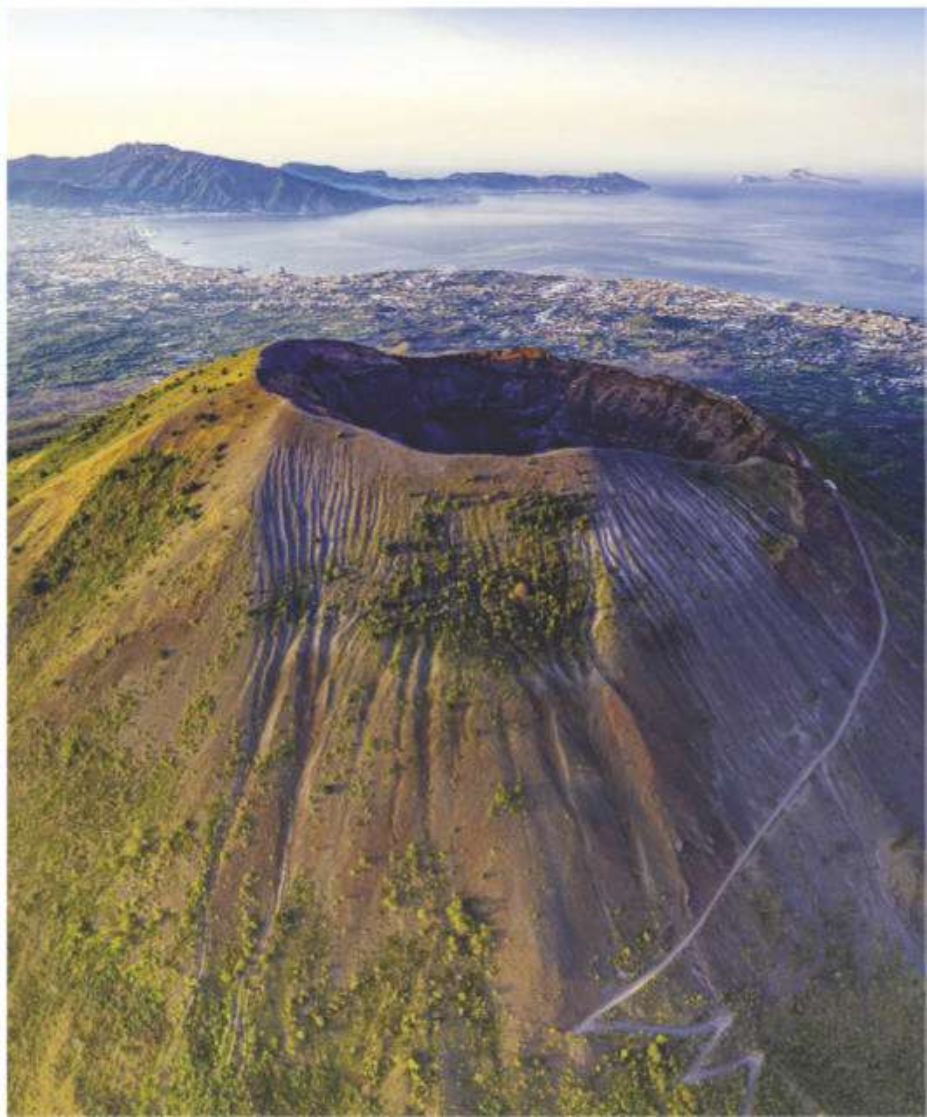
Recent advances in imaging technology are enabling muon tomography to find a growing range of applications (see 'Structural integrity', p52), but the technique isn't new. The engineer EP George used it to check the amount of material above a mine in Australia in 1955, fewer than 20 years after the muon had been discovered (by Carl Anderson and Seth Neddermeyer in 1936). And before the end of the 1960s the renowned American physicist Luis Alvarez was using muon tomography to look for hidden chambers in pyramids.

ALAMY, SCANPYRAMIDS MISSION, GETTY IMAGES

ABOVE Some members of the ScanPyramids team set up one of the project's muon detectors in front of the north face of the Pyramid of Khufu

LEFT Additional muon detectors were placed within the Pyramid of Khufu, including this one positioned inside the Queen's Chamber

BELOW The Mount Vesuvius volcano, another subject of muon tomography investigation, looms over the Italian city of Naples



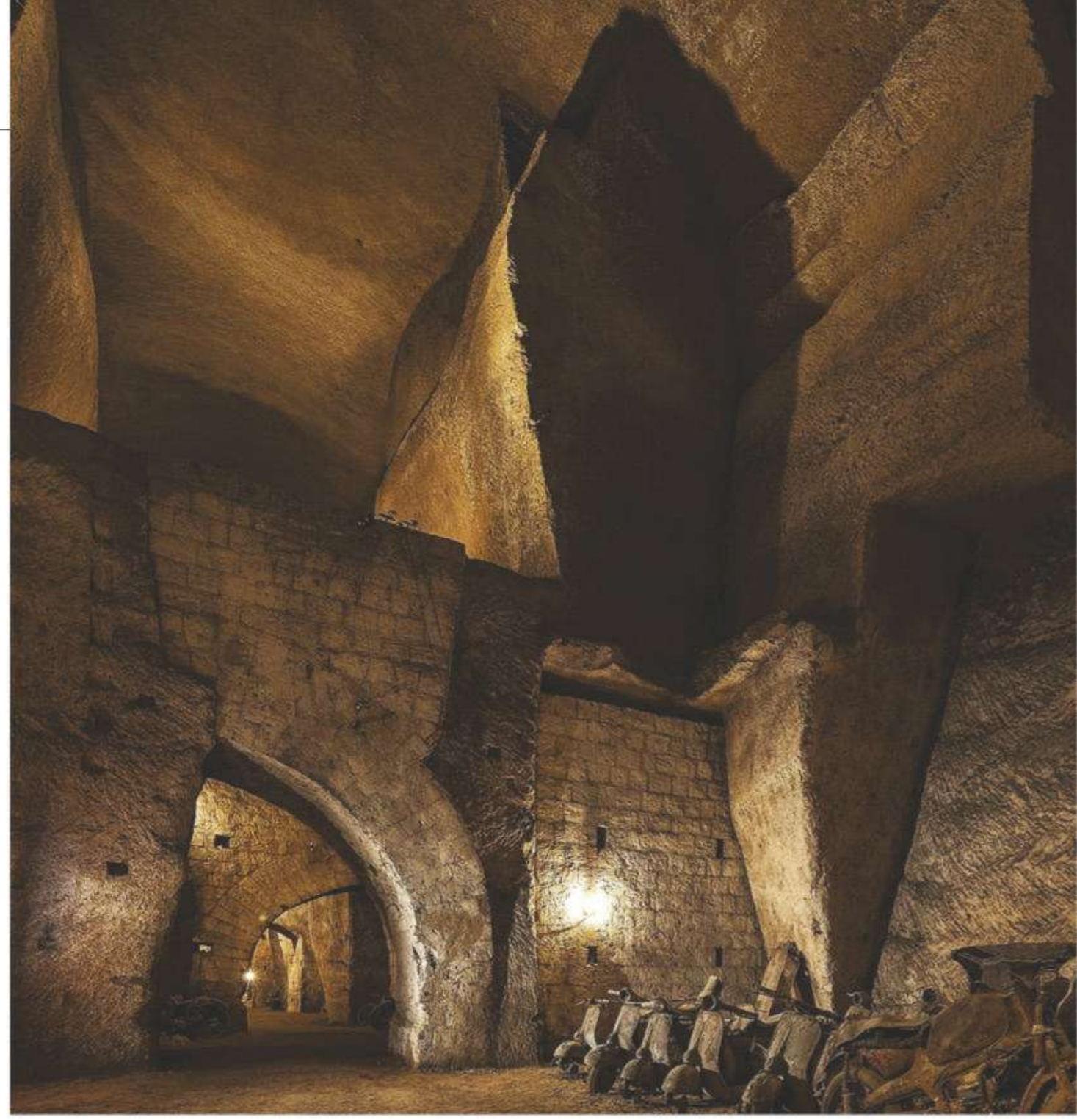
STRUCTURAL INTEGRITY

Muon tomography's ability to detect density differentials inside an object gives it plenty of potential applications outside of archaeology and volcanology. Cavities and cracks inside structures often equate to areas of weakness, so if they can be identified within buildings, bridges and other large civil-engineering structures, it could save lives.

Being non-invasive means such areas of weakness can be identified without drilling, which could harm the structure further. It's for this reason (and the historical significance) that an examination of the dome on the Basilica di Santa Maria del Fiore in Florence (pictured above) using muon tomography has been planned.

Similarly, using muon tomography to check the thickness of walls of blast furnaces (used to smelt metals) provides clues as to the specific appliance's remaining lifespan.

The technique is also finding uses at nuclear power stations. At Sellafield, it's being employed to check containers of nuclear waste, which would otherwise have to be opened, creating further radioactive waste needing to be safely repackaged.



ABOVE The Galleria Borbonica, one of the subterranean structures bored out of the tuff beneath Mount Echia. It was used as a bomb shelter during WWII and has also been used by local police to store impounded vehicles

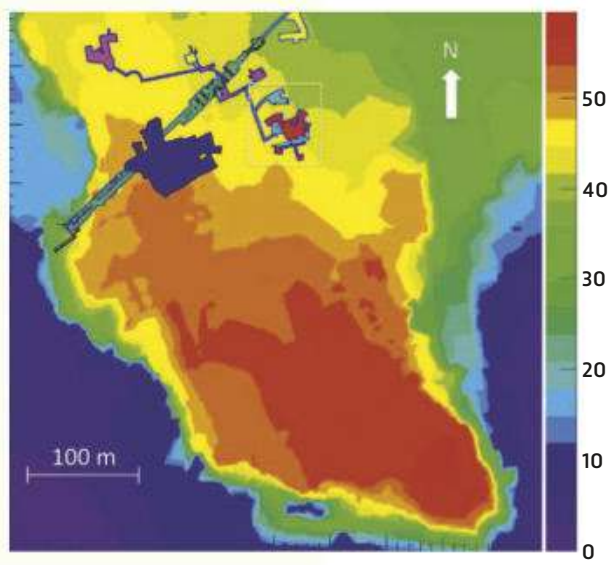
"If you look at the original paper by Alvarez, and his measurements of the pyramid, he did absolutely everything right," says Kaiser. "It was very cleverly done. He didn't find any cavities, but he was just unfortunate to be looking in the wrong pyramid."

Alvarez was looking inside the Pyramid of Khafre. Had he set his detector up next door, at the Pyramid of Khufu, he might have beaten the ScanPyramids project to the punch by almost 50 years.

All of this goes some way towards explaining why muon detectors are appearing at a growing number of archaeological sites. With improving imaging processes offering higher resolution pictures and cheaper, more portable detectors being developed, muon tomography is expanding our scope for exploration by providing us with a window – a window that gives us a glimpse into places we can't go.

And there's no shortage of such places. Mount Echia, in Italy, for example, is a 60-metre-high rocky headland that extends into the Gulf of Naples. It's a built-up part of the city today, but almost 3,000 years ago, in the 8th Century BC, it was the site of Parthenope, the Ancient Greek colony that would later become Naples.

The headland largely consists of tuff, a soft, yellow rock made from volcanic ash, that's often used in ancient constructions. As such, a complex system of tunnels and caves exists beneath Mount Echia, where generations of people have excavated the tuff to use as building material.



ABOVE LIDAR observations of Mount Echia provide some indication of the complex of structures lying beneath the area

GETTY IMAGES, WIKI COMMONS, GIULIO SARACINO

Investigations of the tunnels and caves have been underway for years, but in 2017 a team of physicists from Naples and Florence realised Mount Echia's characteristics would make it the ideal location to test the muon detector they'd been developing – partly because so many of the cavities are already known (so the team would have something to verify their results against), but also because it's not just ground the cavities are buried under.

"Mount Echia is not an isolated hill; it's completely covered by buildings," says Prof Giulio Saracino of the University of Naples Federico II and Italy's National Institute of Nuclear Physics (INFN). "So it was not an easy test. But it was a very interesting one because it wasn't clear at the beginning if all the buildings would interfere with the measurements."

Nevertheless, the test was successful: not only was the team able to identify a selection of the known cavities, they also found signs of a new, previously hidden one. "We discovered the new cavity, reconstructed it in three dimensions and were able to give the speleologists [cave experts] a sense of its position underground, because there's no way to reach it at the moment," says Saracino.

"Not only was the team able to identify a selection of the known cavities, they also found signs of a new, previously hidden one"

PROJECTS POSTPONED

From Mount Echia, the team moved on to another cavernous archaeological site in Cuma, a town near Naples believed to be the location of the first Greek colony on mainland Italy. Work there was interrupted by the COVID-19 pandemic, which is just one of the obstacles to muon tomography investigations – because not only are the right geographical and topological characteristics required, but the political situation needs to be amenable too, as Prof Nural Akchurin from Texas Tech University explains.

"We were trying to get our first prototype [muon detector] into Turkey to image an archaeological site in Limyra. But the politics in Turkey were messy; there was a coup attempt [in 2016] and a lot of things came to a screeching halt for a year or two … So we said, 'Okay, let's just work on a second prototype,' because we need to improve things. But we haven't given up on deploying our instruments somewhere in Turkey and there are a couple of candidate sites. Right now, we're testing things in the lab. But, in short order, we could deploy our detectors – maybe this summer, if COVID allows."

COVID has also affected the ScanPyramids project. Prior to work being suspended in 2020, continuing muon tomography at the Pyramid of Khufu had revealed more of the smaller cavity discovered in 2016 (suggesting it's a corridor extending at least five metres into the pyramid, possibly angled upwards) and refined the estimated dimensions of the big void discovered in 2017 (it's now thought to be at least 40 metres long).

If the global rollout of COVID vaccines goes according to plan, it's possible work could resume on the ScanPyramids project, and the others, soon. And when it does, more of the secrets hidden inside some of the world's oldest natural and human-made structures could begin to reveal themselves. **SF**

by **ROBERT BANINO**
Robert is a freelance science writer based in Bristol.

DESTINATION

3,000m
ABOVE SEA LEVEL
DARK STAR CAVE

CONQUERING THE UNDERGROUND EVEREST

The Dark Star cave system in a remote corner of Uzbekistan might one day be crowned the 'world's deepest cave'. Hidden inside the subterranean labyrinth lie geological time capsules that hold the secret to Earth's past and future climate...

WORDS **JHENI OSMAN** IMAGES **ROBBIE SHONE**

"Oranges, reds, yellows... a kaleidoscope of colour. It was like walking in the Alps in autumn. Truly amazing." Israeli geologist Boaz Langford is describing one of the vast caverns in Dark Star – a huge cave system tucked inside the Baisun-Tau mountain range in an isolated region of Uzbekistan. Langford was part of the international team of scientists and cavers who explored the system in 2014.

"In another branch there are frozen lakes; elsewhere, huge waterfalls. The variety of sights is incredible. Every area is different. Dark Star is like no other. Totally unusual. I'm a scientist, and not very religious, but there is something spiritual about that place."

Political instability and its remote location have kept the depths of Dark Star (named after a 1974 sci-fi comedy film) hidden from human eyes. But in 1990, a British team managed to reach one of the entrances ▶

Cathedral-like spaces open up inside the Dark Star cave system hidden within Uzbekistan's Baisun-Tau mountains

and so exploration of this dark underworld began. Around 17km of passages, along with additional entrances, have since been discovered, but all of the openings sit halfway up a 200m-high limestone cliff. And just getting to the base camp at its foot is a long and treacherous journey.

Langford and his colleagues met the rest of the expedition team in the Uzbek capital Tashkent. Loading all their equipment onto a bus, they drove 160km along part of the ancient Silk Road towards Samarqand, before switching to a six-wheeled truck and heading south across arid plains in the direction of the Baisun district on the Afghan border. At the foot of the Baisun-Tau mountain range, they ditched the truck and continued on foot for two days, with donkeys lugging their gear.

"The path was so treacherous that one of the donkeys fell down a cliff and died," says Langford. "One of the team had to climb down to the poor beast to recover our equipment."

Eventually, the team reached a point where it was too tricky for the donkeys to continue, so they hauled the kit the rest of the way to base camp themselves. From the base camp, it's still a two-hour hike followed by a 100m rope climb to reach the jaws of Dark Star.

TOP It took a treacherous two-day hike into the Baisun mountain range to reach base camp

TOP RIGHT Finding entrances to Dark Star requires rappelling partway down a cliff face

RIGHT Blue ice is a common sight in the caves, even when temperatures outside are as high as 37°C

CLIMATE CLOCK

Why are scientists bothering to traipse for days across inhospitable terrain to reach a remote corner of Uzbekistan? What could possibly be lying in the depths of the cave to make all this hardship worthwhile?

The answer: an accurate climate clock.

Information about Earth's past and future climate is captured in cave mineral deposits. These are made from flowing or dripping water laden with minerals – calcite, aragonite and gypsum. Over time, the minerals build up to create rock formations called stalagmites and stalactites.

"By analysing such cave mineral deposits, I can go into the past and learn more about how the local climate evolves, and how that reflects regional or global changes," says Dr Sebastian Breitenbach, a palaeoclimatologist at Northumbria University, who's currently working on samples from Dark Star.

"The [usual] 'radiocarbon clock' only works back to about 40-50,000 years and then it's over because there's no radioactive carbon left to count. Beyond 40,000 years, we have very little information about past climate in terms of chronology. But the great advantage of using cave deposits is that we can use other

"FROM THE BASE CAMP, IT'S STILL A TWO-HOUR HIKE FOLLOWED BY A 100M ROPE CLIMB TO REACH THE JAWS OF DARK STAR"

radioisotopes, such as uranium, which have a longer decay chain. This basically means that we can track the time accurately to about half a million years.

"Both uranium and lead can be present in stalagmites. And we can leap even further back if we use uranium-lead, because lead is stable – theoretically, we could date back to the Big Bang. And once you have the dating, you have a chronology, and can use climate proxies to look into how the climate – and environment – evolved."

In short, stalagmites are great climate archives because they grow in caves all over the world, relatively undisturbed for millions of years, isolated from external factors, such as extreme weather and human or animal interference. But getting a good sample from such remote settings back to the lab can be challenging – if the stalagmite breaks, it's a long, *long* journey back to get another one.

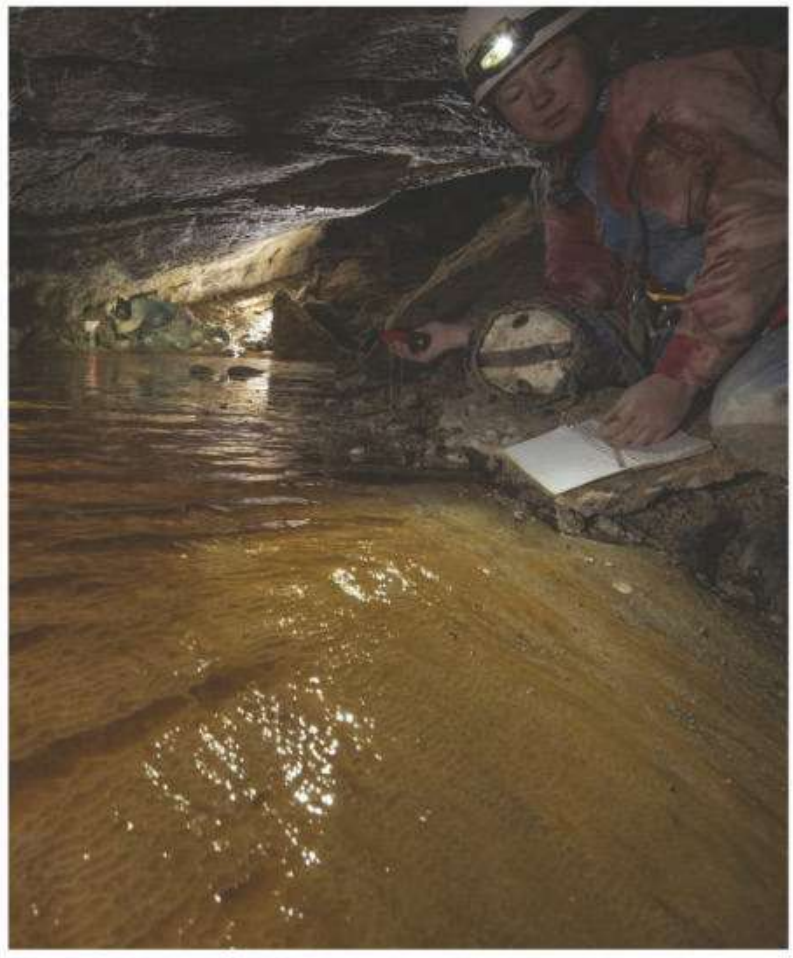
PREDICTING CLIMATE CHANGE

All of these palaeoclimate records can be used to understand the past and predict the future. Indeed, archaeologists are using Breitenbach's results to solve the puzzle of how modern humans and their predecessors migrated back and forth across Asia – and what drove their migration.

"Archaeologists want to understand how humans interact with nature and how climate impacts decisions on when, how and why they moved," says Breitenbach.

"Temperature was not a problem for modern humans, Denisovans or Neanderthals. The key was water. Palaeoclimate records built on stalagmites are our best bet to discover which time intervals were suitable for human habitation and which were more hostile."

Meanwhile, scientists are also using palaeoclimate records from cave sediments to predict future climate change and, crucially, water supplies in the region. Mountain ranges such as the Himalayas are, in essence, the water towers of the world. And if ice contained in the region's glaciers and permafrost is lost, rivers like the Ganges will dry up, cutting the water supply to people ➲



TOP Charting and mapping the cave system is as much of a priority as taking samples of the minerals inside it

ABOVE At 250m long, Full Moon Hall is the largest known chamber in the Dark Star cave system

RIGHT More than a mile inside the mountain, where the temperature is around 2°C, the team pitch tents for the night

in the surrounding countries, such as Uzbekistan, Kurdistan, India and China.

"Stalagmite records, like tree-ring records, are often very detailed and well dated," says Dr Alex Baker, from the National Centre for Atmospheric Science at the University of Reading.

"This is important because they can tell us how rapid past episodes of regional climate change were and how quickly the climate was able to recover. This information can be used to estimate how glacier retreat might be curtailed if and when greenhouse gas emissions are meaningfully reduced. Such estimates can be highly uncertain, so continued development of climate models and better palaeoclimate records are always needed."

Furthermore, using stalagmite records as a reference, scientists can see how well a climate model matches the records for the last few decades and predict climate change in the next few.

"Palaeoclimate records of the recent past are particularly useful in remote regions, where instrumental data from meteorological stations are either sparse or less reliable, due to difficulties in performing measurements in challenging environments," says Baker.

"They also help us understand natural variability in the climate system and to place the changes we're observing into a longer-term context. Often this allows us to go one step further and establish whether those changes are beyond the natural variability of the recent past and driven instead by human activities."

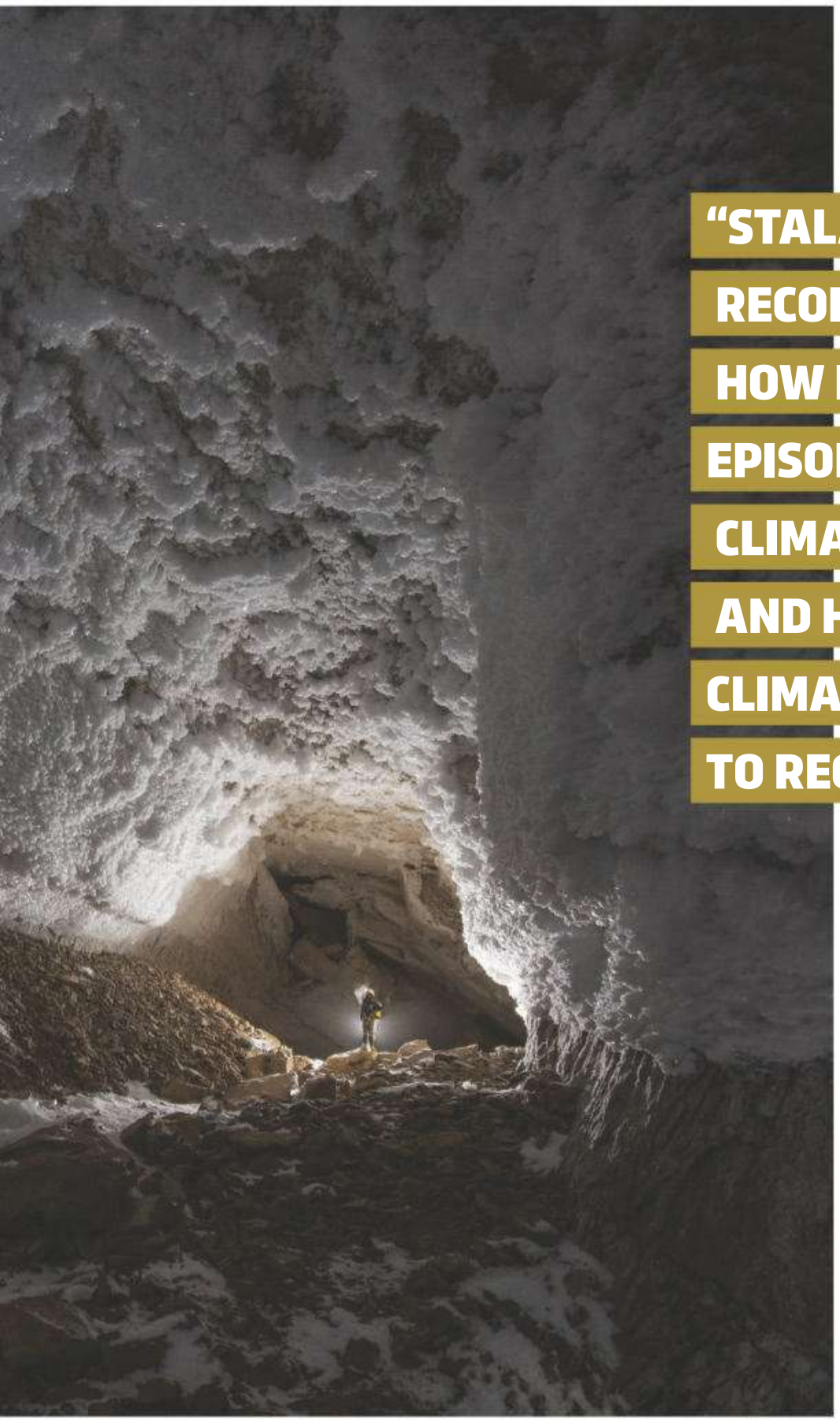
DELVING DEEPER

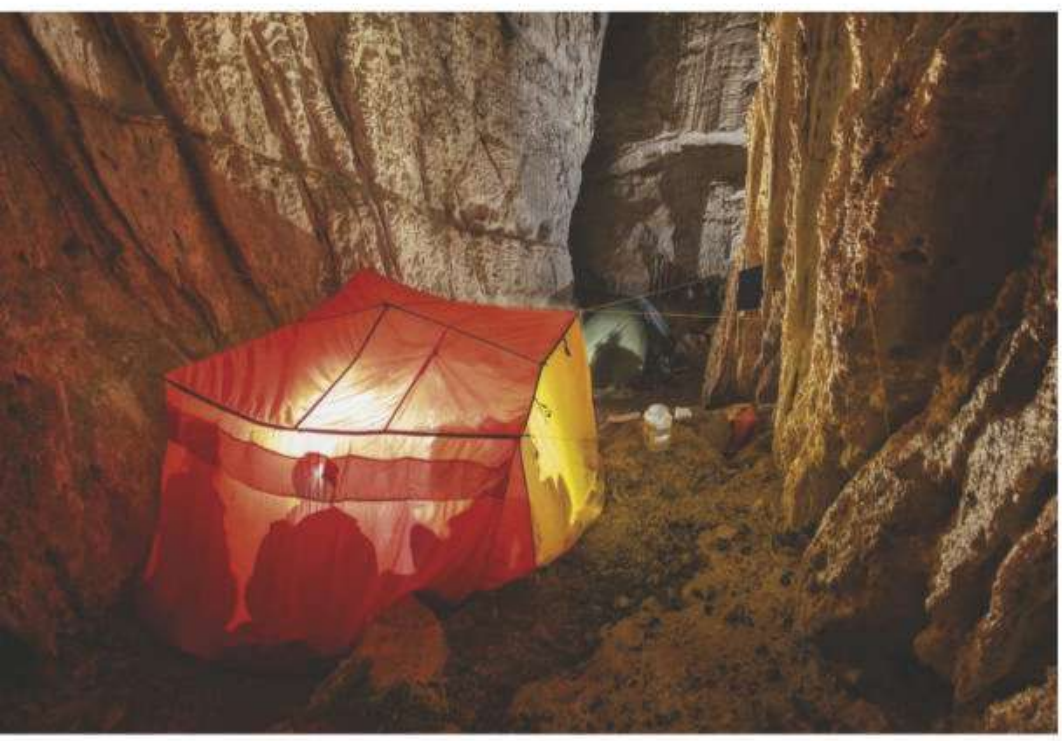
Back inside the Dark Star cave system, Langford and his colleagues were tasked with mapping uncharted terrain and establishing a new base camp. The expedition had already set one up at a depth of 450m, but they were hunting for a good spot deeper underground.

They spent five days exploring passages, stumbling upon new chambers and surveying – using laser distometers to take measurements, which were then fed into a tablet to generate maps. When passages became too narrow, the team used their engineering skills to 'nibble through' the rock and make them fractionally wider. Their tenacity paid off and they found a spot 800m down, with a water supply and flat enough to erect tents on.

Deep inside the cave system there's no natural light, so it would be easy to lose track of time. Explorers tend to keep to the same timing as on the surface. When it comes to food, everyone below ground cooks for themselves.

Water is in ready supply and the cavers drink directly from streams in Dark Star. In cave systems elsewhere, water often has





"STALAGMITE RECORDS CAN TELL US HOW RAPID PAST EPISODES OF REGIONAL CLIMATE CHANGE WERE AND HOW QUICKLY THE CLIMATE WAS ABLE TO RECOVER"

to be boiled to make it potable, as base camps may be directly under one another and the water flowing down becomes polluted from the 'toilet' above.

One issue in Dark Star is the cold. Hypothermia is a problem and can strike very quickly. "Outside it can be 20°C and inside close to zero," says Langford. "You have to be kitted out ready to work super-fast against the cold. And, when you're not working, you can get really cold during the night. If the underground base camp is full – say, five people – then great, you're warm. But if it's just three people, you need a good sleeping bag."

To some people, such an adventure may sound exhilarating. To others, the idea of sleeping in freezing temperatures and wriggling along narrow passages might sound petrifying. After all, there are horror stories of cavers getting lost and never being seen again. No such fate has befallen any expedition member venturing into Dark Star – or, at least, not yet.

But Langford says most cavers are like him and never get nervous about an expedition: "Honestly, I'm just super-focused about it. I don't think about the possibility of getting injured or lost or something like that. I just follow the mission. You need colleagues you can rely on when exploring to help you out if you get in a tricky situation. And you need someone to share your experience with – someone to chat to in the evening. A caving expedition is a really social experience."

GET THE RECORD

Experts believe there's still a lot left to explore and discover in Dark Star's hidden depths. Maybe one day it'll even take over the title of world's deepest cave from the current holder, the 2,212m-deep Veryovkina Cave in Georgia.

But the bigger prize than the world record is gaining invaluable palaeoclimate records from any of the caves in the area. As Breitenbach says: "We still have so many questions to answer and gaps in our climate record. We need to go back to the region because some samples don't cover important time intervals. The whole Baisun-Tau mountain range may become a pillar for palaeoclimate reconstruction."

Indeed, palaeoclimate records are vital to understanding past climate variability and are the key to predicting future climate change. The lives of so many depend on it. **SF**

by **JHENI OSMAN**
(@jheniosman)
Jheni is a science writer and broadcaster, and the author of The Little Book of Big Explorations *(£12.99, Michael O'Mara).*

Only 24 people have ever travelled to the Moon, the last being the crew of Apollo 17 in 1972. That number is set to grow in the coming years

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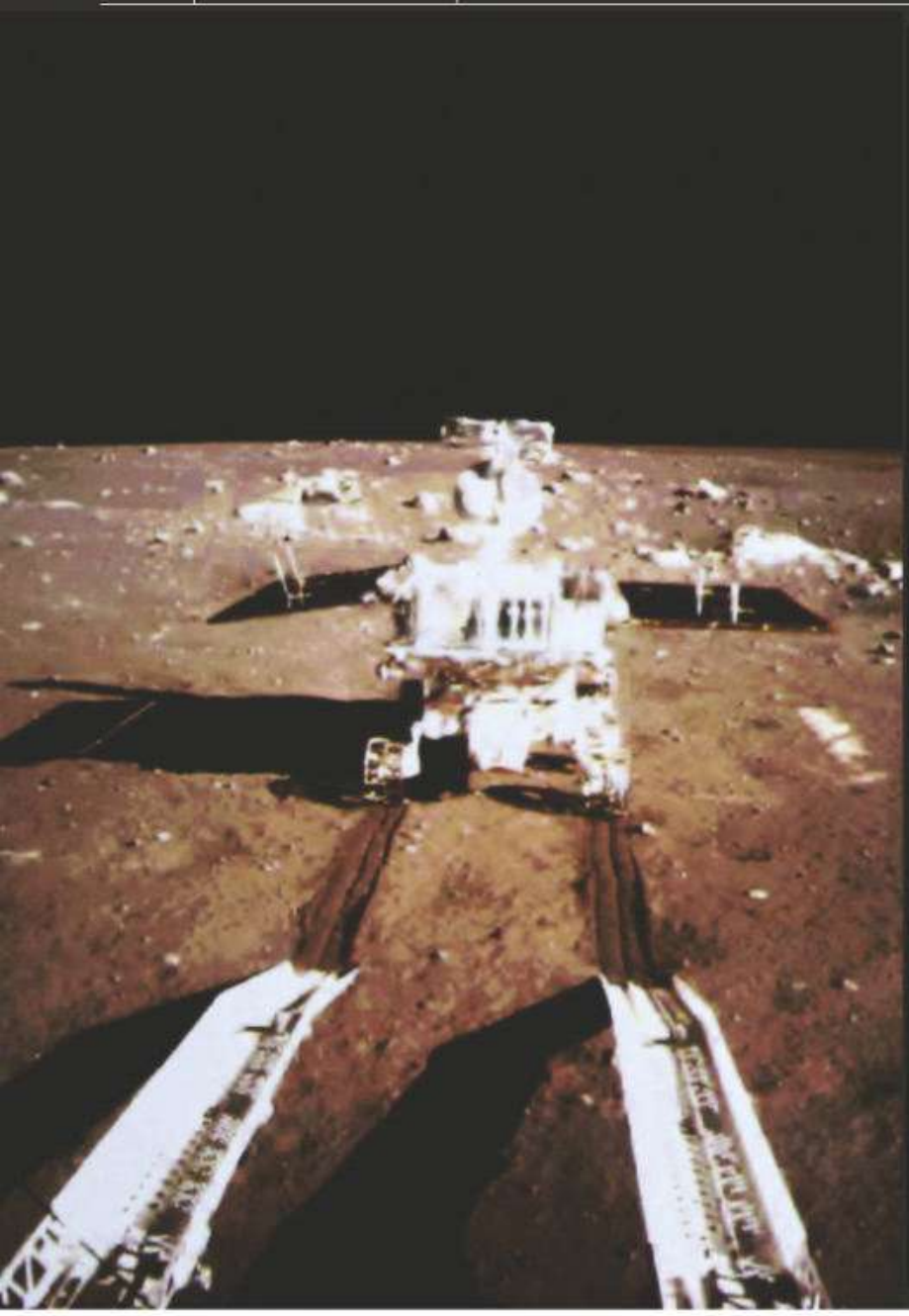
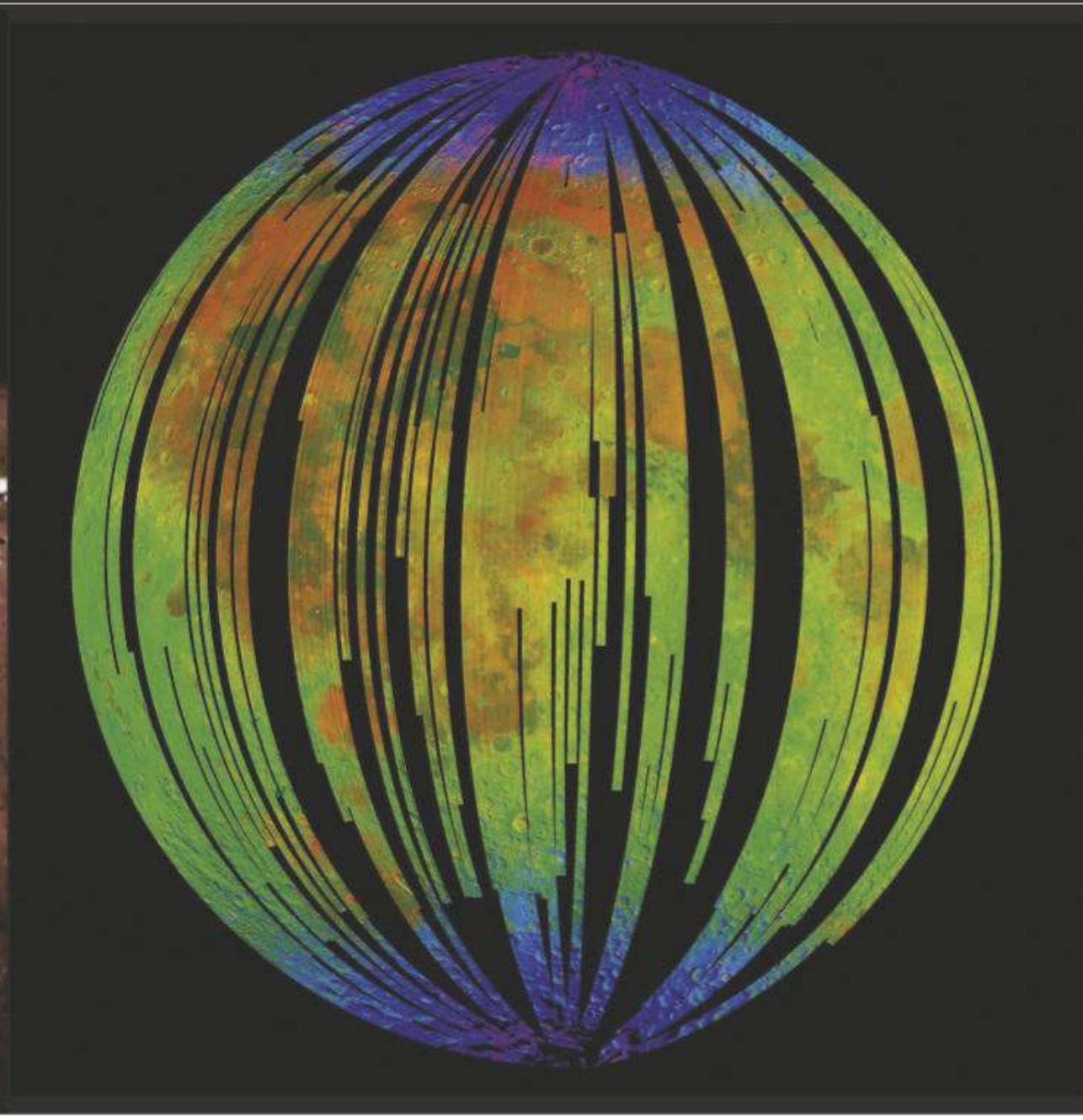
GOING BACK TO THE MOON

The next few years will see an explosion of lunar explorers. But what will they be looking for when they get there?

WORDS **DR EZZY PEARSON**





For almost 40 years, our nearest cosmic neighbour, the Moon, was left alone as we looked elsewhere in the Solar System. That changed in 2013, when China's Chang'e 3 lander touched down on the lunar surface. Since then there's been an explosion of interest in the Moon. NASA, China and even private companies are racing back to it, with dozens of robotic and human missions being planned. Things are set to get a lot more crowded on the lunar surface over the coming decade, but this time, we'll be staying.

"We know the Moon has potential resources that will be useful for space exploration," says Ian Crawford, a professor in planetary science from Birkbeck, University of London. "Particularly water ice trapped in the very dark shadows of craters at the poles."

Unlike Earth, the Moon's axis isn't tilted at a large angle, so the Sun is constantly overhead when you're at the lunar equator.

ABOVE LEFT China's Chang'e 3 lander, and its Yutu rover payload, touched down on the Moon on 14 December 2013 – the first craft from Earth to do so for almost four decades

ABOVE RIGHT NASA's Moon Mineralogy Mapper detected water deposits (in blue) near the lunar poles in 2018

If you're at the lunar poles however, the Sun's always on the horizon, creating long, permanent shadows in the surrounding craters. Hidden from the Sun for billions of years, temperatures in those craters are low enough that water ice has been able to survive in them and it's this that's captured everyone's interest.

THE KEY TO GOING FURTHER

"Water is an extremely useful substance for space exploration, certainly in the context of human exploration," says Crawford. "It's a requirement for life, but can also be broken down into oxygen and hydrogen. Combined, they're a useful rocket propellant."

Though planetary geologists have seen signs of lunar ice for years, the first definitive proof of the presence of water came in 2018, following detailed analysis by NASA's Moon Mineralogy Mapper on the Indian lunar orbiter Chandrayaan-1.

While we have plenty of water here on Earth, it's heavy – each cubic metre weighs 1,000kg. Launching it into space takes a huge amount of energy. If, instead, we could find a way to harvest water beyond Earth's gravitational pull, it would allow for bigger and more ambitious projects, both on the Moon and beyond.

"If we're going to engage in a programme of human space exploration, the Moon is the obvious place to start," says Crawford.

While there appears to be water at both poles, it's most concentrated in the south. A region known as the South Pole-Aitken Basin – the Moon's largest impact crater – is home to several large deposits of ice. What's not clear, however, is what form the ice takes.

SHUTTERSTOCK, GETTY IMAGES, NASA/DOMINIC HART

"We're still in the initial prospecting phase," says Crawford. "We don't know whether we should be investigating big blocks of ice here and there, or just tiny, micron-sized grains of ice mixed in with the lunar soil."

NASA is planning a mission to send the Volatiles Investigating Polar Exploration Rover (VIPER) to the Aitken Basin in 2023. Once there, it will drive into the shadow of one of the craters to investigate the ice on the surface and, with its drill, two metres below it.

The water is also of particular interest to scientists. As it has remained undisturbed for millions, or sometimes billions, of years, it gives planetary geologists a window into the past.

"The Moon is very ancient and geologically inactive, which means that it's sort of a museum to the evolution of rocky planets – [its rocks hold] a record of its earliest evolution from shortly after its formation," says Crawford. The ice could act as an archive, detailing how water was brought to the Moon by comets and asteroids. As these would have also carried water to our planet, such an understanding would tell us as much about the history of Earth as it does the Moon.

"If we're going to engage in a programme of human space exploration, the Moon is the obvious place to start"

ABOVE NASA is developing the VIPER rover to explore craters near the Moon's south pole and inspect any ice it finds on, and under, the lunar surface

LOCATION, LOCATION, LOCATION...

While many missions would like to follow the water and explore the polar regions, this isn't without its challenges. Until now, most lunar missions have touched down around the sunlit equator where solar panels can easily supply power. It's much trickier when you're heading somewhere that's in permanent darkness.

Some early missions, such as VIPER, will use rechargeable batteries to undertake brief sojourns into the shadows, but longer-term missions will require more thought. If future astronauts plan on mining the lunar ice, they'll need a permanent base to do so and that will require a very specific location to prosper.

"The best place, if you could find it on the Moon, would be a permanently shadowed area with water, near a peak with persistent light that could stay sunlit almost all year for power

from solar panels, and a cave for shelter," says John Thornton from Astrobotic, the company contracted by NASA to transport VIPER to the Moon. "Caves provide a nice, thermal environment underground. If we could find that location, there's no doubt that's going to be the place where a human settlement pops-up."

Once a spot is found, it then becomes a case of building a base. Initially, this will probably be done with structures transported from Earth, though weight and size restrictions on launch vehicles will limit what can be sent, so it would be much better to build a base in situ. Fortunately, there are building materials everywhere on the Moon. Several projects are looking at harvesting regolith – the fine layer of dust created by micrometeorites pulverising lunar rocks – and using it to 3D print structures.

In the longer term, it could be possible to extract iron and titanium from lunar rocks. We'd need to build a refinery to process them, but having access to such metals beyond Earth's gravity would allow us to build much larger structures and spacecraft. The Clementine spacecraft, launched in January 1994, detected the highest levels of the metals around the lunar mare – the dark regions created by ancient lava flows. As an added bonus, most of the ores are oxides, so they'd produce oxygen as a by-product.

But not all potential lunar resources are as easy to extract. There are an estimated billion tonnes of helium-3, a potential fuel source, on the lunar surface, but extracting it would require a huge industrial complex mining hundreds of tonnes of regolith

WHO OWNS THE MOON?

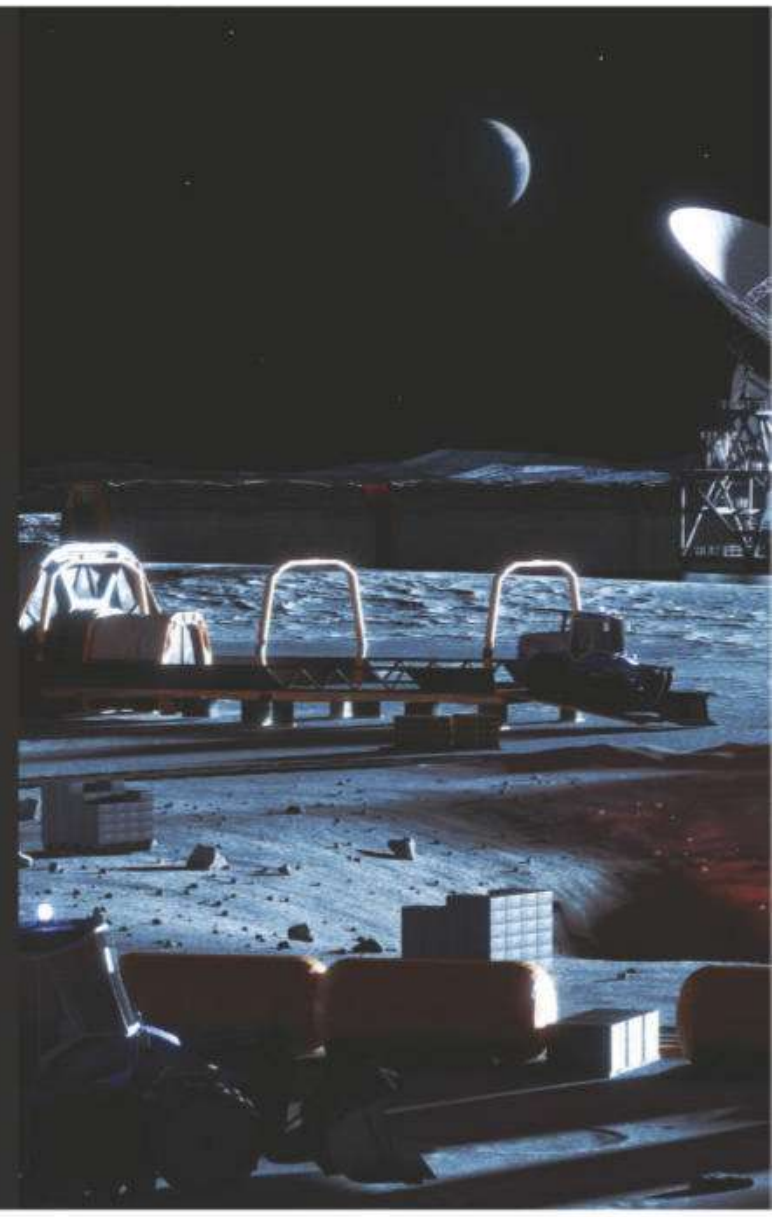
Historically, lawless colonisation of a new land has rarely ended well. While there are no indigenous peoples or environments that can be harmed on the Moon, the current state of space law could be setting up future lunar colonists for disaster.

Today, the only international law governing space stems from the 1967 Outer Space Treaty that's overseen by the United Nations. This states that no government can lay claim to the Moon, but failed to foresee that private companies may also want to stake a claim. There's no discussion of what will happen if two parties want to set up their bases in the same spot. And when it comes to mining, there's a big grey area over whether the miners would actually be able to claim ownership of the resources they extract.

It's not just the material resources of the Moon that need protecting though. Lunar water is hugely important to planetary geologists, but its irreplaceable record could easily be destroyed.

"Many questions related to the origin of the Moon's water require precise sampling and cold-storage with return to Earth for detailed chemical analysis," says Dr Julie Stopar from the Lunar and Planetary Institute. "While science and industry can work together to study water on the Moon, their goals are often very different. Scientists may require precise knowledge of chemical compositions of small quantities of water and soil, whereas industry might seek to process large quantities of water-ice or water-rich soil, with no concern for trace chemical signatures."

Science fiction might have predicted a high-tech utopia being established on the lunar surface, but could the reality end up being more like the Wild West, with prospectors fighting over the choicest water deposits? Only time will tell.



every second – a prospect that's centuries away from being feasible, even under the most ambitious circumstances.

THE NEED FOR COLLABORATION

Such ambitious plans can't be undertaken alone, however. Currently there are two superpowers working to put humans on the Moon: the US and China. Though US law prevents the two from collaborating, they're both reaching out to other nations to help them achieve their goal.

"Lunar exploration can become a tremendous focus for international cooperation, which I think would be highly desirable, especially in today's international climate," says Crawford.

Despite having only sent its first 'taikonaut' into space in 2003, China's space programme is making great strides. Its Chang'e series of robotic lunar missions has been wildly successful and saw the first landing on the far side of the Moon in 2019 (Chang'e 4) and plans to return the first samples from the lunar south pole with Chang'e 6 (due to launch in 2023). The Chang'e 4 mission carried instruments from the Netherlands, Sweden and Germany, while European astronauts have already run several training exercises alongside their Chinese counterparts. Though the Chinese are secretive about their precise plans, they've made it clear that these missions are a precursor to a lunar landing mission.

With several decades more experience to call upon, the US efforts are a little more mature. Their current plans are centred around the Gateway, a lunar station that would orbit the Moon. The station would act as a staging post for missions to the lunar surface, and potentially Mars and beyond. The Japanese, Canadian and European space agencies have all signed up to help, agreeing to build parts of the station on the promise of one day sending their own astronauts to the Moon. The first sections of the Gateway are due to fly in 2023, with operations starting in 2026. Meanwhile NASA is already planning the Artemis mission, which will send the first woman to the lunar surface by 2024.

These ambitions are also helping to foster a branch of space exploration that's blossomed over the last decade: private enterprise. To encourage the growth of the space sector, NASA set up the Commercial Lunar Payload Services initiative, asking companies to transport the space agency's science instruments to the Moon.

"NASA has plans to buy at least two lunar missions per year for the next eight to 10 years," says Thornton. "This is a first step towards commercialisation of routine, regular transport to the Moon."

As well as being much cheaper for NASA, it also creates opportunities for those with a much smaller budget. In late 2021, Astrobotic will be sending its Peregrine lander to the Moon with a dozen NASA instruments, but it also has room to transport other projects at the cost of $1.2m per kilo (approx £850,000). That might sound a lot, but in spaceflight terms it's a bargain.

"We have a broad array of customers, even just on our first mission," says Thornton, who has seen universities, companies and even private individuals sign up to hitch a ride. "We have a payload from the UK that's actually a fun little walking rover that's going to walk across the surface."

Alongside Astrobotic are many other companies all preparing to head to the lunar surface. Though none of them has successfully landed yet, there's no shortage of passengers waiting to hitch a ride. The lunar surface is about to get busier than it's ever been. **SF**

SCIENCE PHOTO LIBRARY X2

LEFT Lunar habitats could be built using inflatable structures covered with a shell, made from 3D printed regolith, to shield the occupants from radiation

BELOW A lunar mining operation faces a number of challenges, not least of which is who owns the material it would seek to extract

by **DR EZZY PEARSON**
Ezzy is the news editor of BBC Sky At Night Magazine. *Her first book,* Robots In Space *(£20, The History Press), is out now.*

DESTINATION

2-4AU*
FROM EARTH

PSYCHE ASTEROID

MISSION TO A METAL MINI-WORLD

There's a giant metal asteroid floating out beyond Mars that might be the core of a planet that was smashed to smithereens aeons ago. NASA's sending a probe to find out, but a positive answer could cause even bigger problems...

by DR STUART CLARK

ALAMY

Enormous, metallic and mysterious – the Psyche asteroid is like nothing we've encountered before and could hold clues about the beginnings of the Solar System

*1AU = APPROX. 150,000,000KM

Take a moment to imagine a giant lump of metal, 25 times larger than Mount Everest, floating through space. Finding it difficult to conjure an image? Don't worry, nobody can. That's because no one has ever seen such an object up close before. But five years from now, all will be revealed.

January 2026 is the target date for a new NASA spacecraft to arrive at an asteroid called Psyche. Named after the Greek goddess of the soul, Psyche was discovered on 17 March 1852 by the Italian astronomer Annibale de Gasparis. It's one of the most massive bodies in the asteroid belt between Mars and Jupiter. Modern estimates suggest it contains about 1 per cent of all the mass spread across the millions of asteroids in the main asteroid belt. Yet it's the asteroid's composition that makes Psyche special.

Roughly 230km in diameter and shaped like a potato, Psyche's density is so great that astronomers think it must be made of metal. Also, when astronomers look for the signature of rocky minerals, by analysing the sunlight bouncing off its surface, they can find none of the telltale markers they're looking for.

If Psyche truly is metal, and it's been studied so much now that there appears to be little doubt, then it could hold secrets about the way planets, including Earth, formed 4.6 billion years ago. Unlocking those secrets is what's driving the Psyche mission.

"Modern estimates suggest it contains about 1 per cent of all the mass spread across the millions of asteroids in the main asteroid belt"

PROOF OF ORIGIN

When astronomers turn their thoughts to how Psyche could have formed, there's only one place they know of where such concentrations of metal can exist. And that's in the hearts of rocky planets, such as Earth, Mars and the other worlds of the inner Solar System.

If you could take a slice through one of these worlds, you would find a metallic core, surrounded by a deep silicate layer, known as the mantle, and then a thin rocky crust. Whereas the core is predominantly made of iron and nickel, the mantle features the mineral olivine and the crust is mainly composed of basalt. This layering is produced by a process called differentiation. Differentiation is thought to take place in the final stages of planet formation, when the planets are molten. In this state, dense material, such as metal, sinks to the centre while lighter material, like rock, floats to the surface.

So could Psyche have once been inside a fledgling planet that was smashed to smithereens early in the history of the Solar System? That's what the Psyche mission is designed to investigate. It's a high-stakes game, because if this scenario turns out to be true, astronomers have a lot of explaining to do.

BELOW Crystals of the mineral olivine on a chunk of basalt

"It's called the missing mantle problem," says Dr Julia de Leon, an asteroid scientist from the Instituto de Astrofisica de Canarias, La Palma, and part of the Near Earth Object Modelling and Payloads for Protection (NEO-MAPP) project.

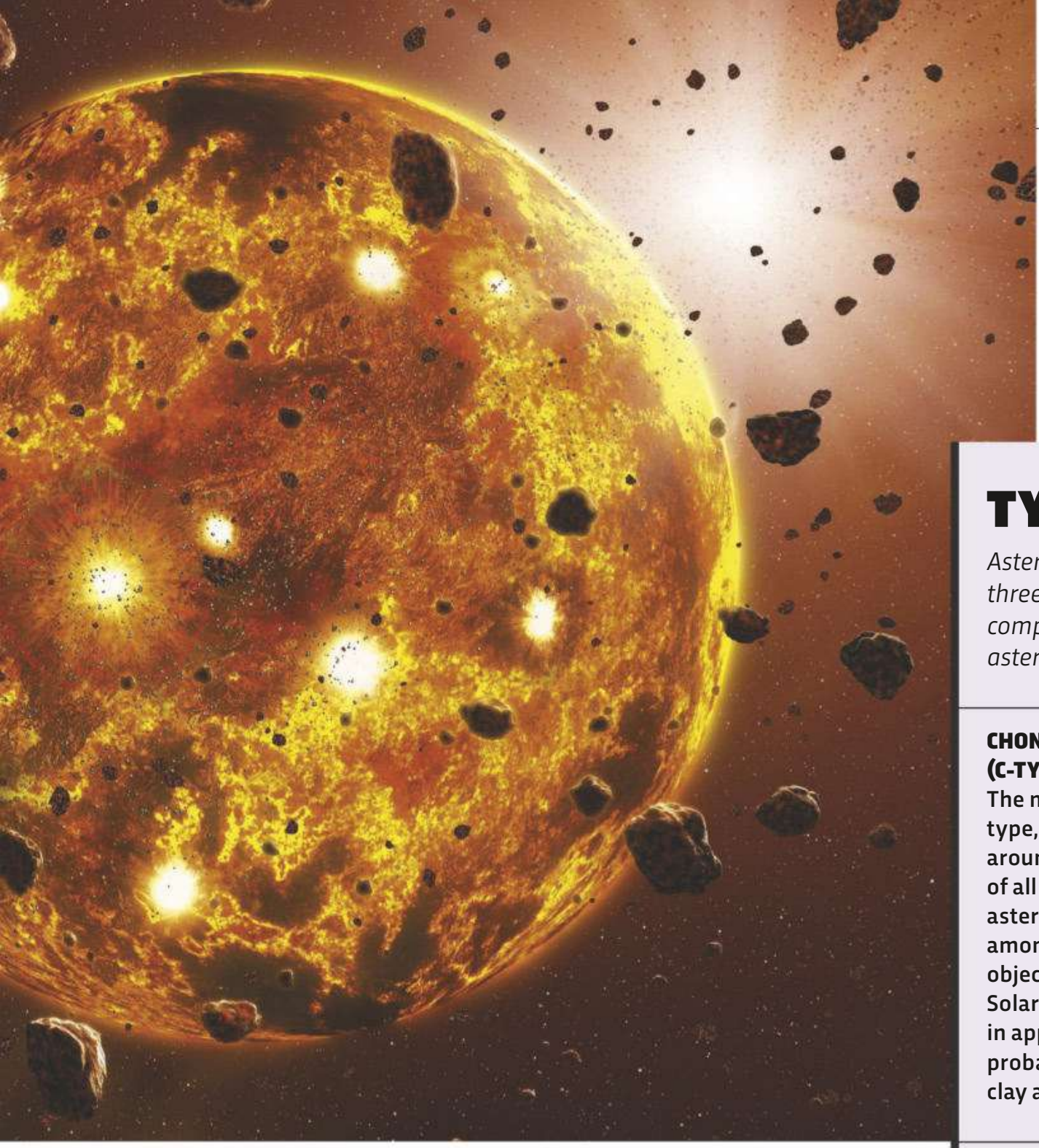
The argument runs like this: if Psyche really was part of the core of a shattered planet, then where's the rest of the debris? Most of the asteroids in the Solar System are primitive, undifferentiated bodies. We see very few olivine-rich asteroids that would represent the mantle material for a shattered world.

It gets worse. A substantial fraction of the meteorites that have been falling on Earth for aeons are made predominantly of iron – exactly as expected from the core of a disrupted world. But when scientists analyse them for traces of other chemicals, the results are so diverse as to be shocking.

"The analysis suggests that the iron meteorites might have come from at least 50 or 60 different cores," says de Leon.

On the face of it, that means 50 or 60 planets that were smashed to pieces during

ALAMY X2, SCIENCE PHOTO LIBRARY X3



LEFT The Psyche mission could help us learn how impacts, explosions and heat combined to form the planets in the Solar System

the formation of the Solar System. It just seems too much considering that astronomers can't find enough mantle fragments to account for even one of these doomed worlds. This is the conundrum that the mission to Psyche must try to unlock.

AN ALTERNATIVE EXPLANATION

The pathway to the mission began a decade ago, when Dr Lindy Elkins-Tanton, a planetary scientist from Arizona State University gave a lecture at the Lunar and Planetary Conference in America. Together with colleagues, she was presenting a new hypothesis for differentiation. In her view, smaller asteroids – rather than almost complete planets – could generate enough heat to at least begin the process of melting and differentiating.

The key to the idea was the mounting evidence that there had been an abundance of aluminium-26, a radioactive isotope produced in the explosion of stars, present at the origin of the Solar System. It suggested a nearby star had exploded shortly before the Solar System began forming.

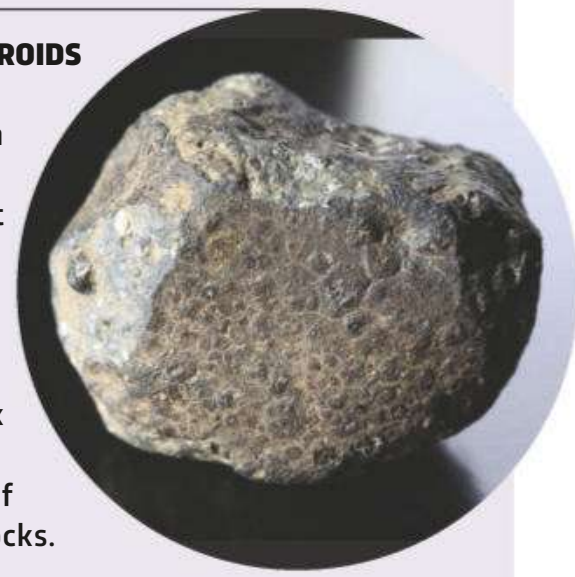
As those first planetesimals formed they naturally included quantities of the radioactive aluminium, and like any isotope its decay would generate heat. This heat then melted the interiors of some planetesimals, allowing them to differentiate on the inside, but, according to Elkins-Tanton, they might not have been completely molten, and so the outside remained undifferentiated.

Hence, when these asteroids were smashed in subsequent collisions, they revealed iron cores, but the surrounding rocks still looked primitive, solving the missing mantle problem. ➲

TYPES OF ASTEROIDS

Asteroids aren't just 'rocks in space'. There are three broad classes of asteroid, based on their compositions: chondritic asteroids, stony asteroids and metallic asteroids.

CHONDRITIC ASTEROIDS (C-TYPE)
The most common type, making up around 75 per cent of all known asteroids. They're among the oldest objects in the Solar System, dark in appearance and probably consist of clay and silicate rocks.

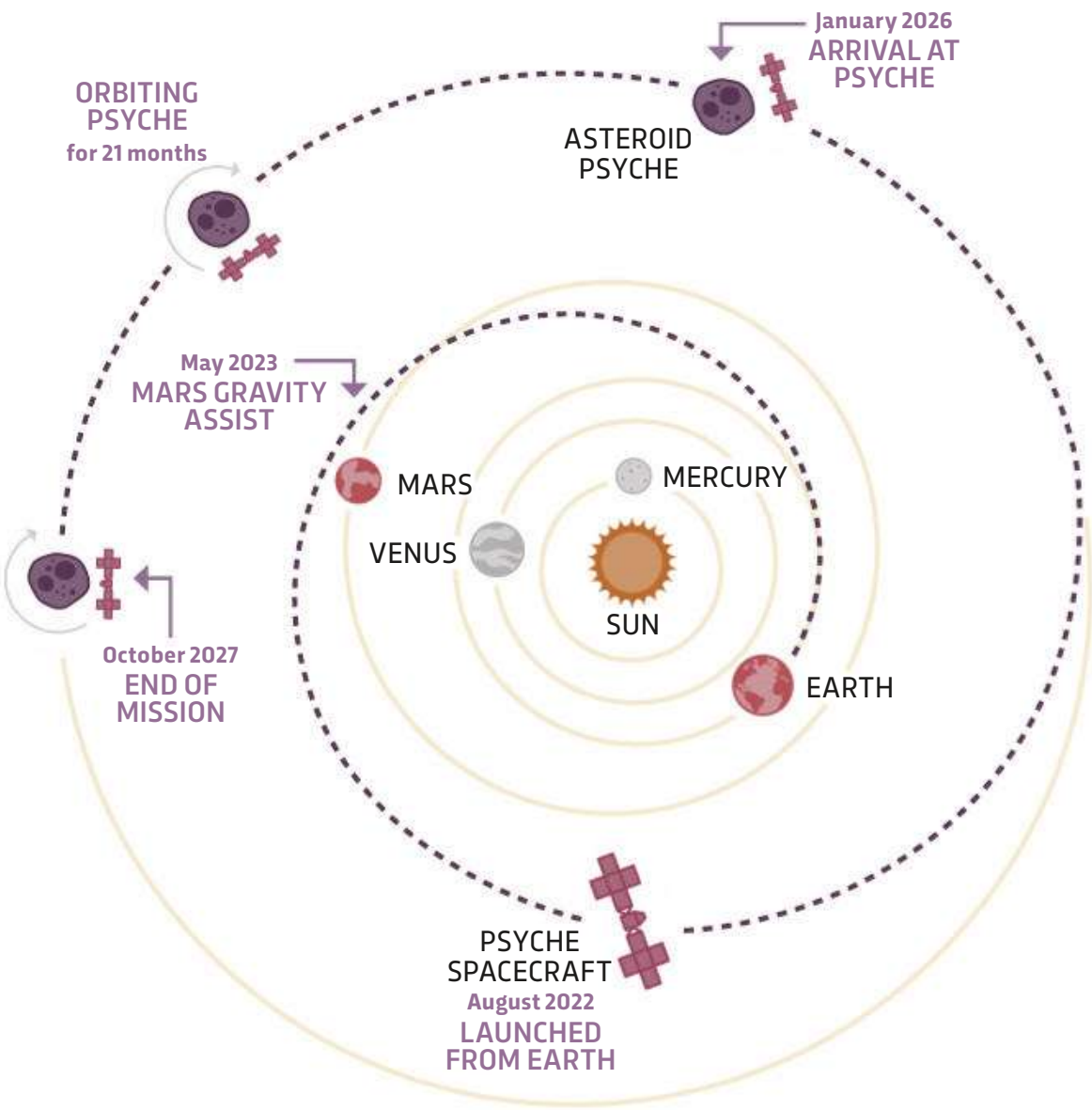


STONY ASTEROIDS (S-TYPE)
Stony asteroids are made up of silicate materials and nickel-iron. They're more reflective than chondrites, but less abundant, accounting for about 17 per cent of known asteroids.

METALLIC ASTEROIDS (M-TYPE)
M-type asteroids are the rarest class of asteroids. Most are nickel-iron, but some appear to be mixed with rocky material. They're thought to have once been inside the cores of early protoplanets.

PSYCHE: MISSION PROFILE

NASA's Psyche mission is currently scheduled to launch in the summer of 2022. This date is critical because the mission needs a gravitational boost from Mars to hoist it into the outer Solar System, and Mars and Earth only come into alignment once every two years. So far, the mission remains on course, despite the problems imposed by the pandemic.



AUG 2022	MAY 2023	JAN 2026	OCT 2027
PLANNED LAUNCH	**MARS GRAVITY ASSIST**	**ARRIVAL AT PSYCHE**	**END OF MISSION**
The Psyche spacecraft will launch aboard a SpaceX Falcon Heavy in August, during its launch window. This will place it on a trajectory to Mars.	Arriving at Mars, Psyche will make a flyby. In the process, it'll pick up enough orbital energy to propel it to its rendezvous with the asteroid Psyche.	Following a 100-day approach campaign, Psyche will arrive to study its namesake from four different orbits, each one successfully closer than the last.	After 21 months of intense science in orbit around Psyche, and with all scientific goals hopefully achieved, the mission will come to an end.

MAXAR, JOHNS HOPKINS APL/CRAIG WEIMAN

The idea sparked a healthy discussion at the conference and an unexpected offer. A couple of scientists from the Jet Propulsion Laboratory emailed her out of the blue to say they would like to propose a mission to test the hypothesis. "Let's go out into the asteroid belt and see if we can find out whether this happened and where it happened," says Elkins-Tanton.

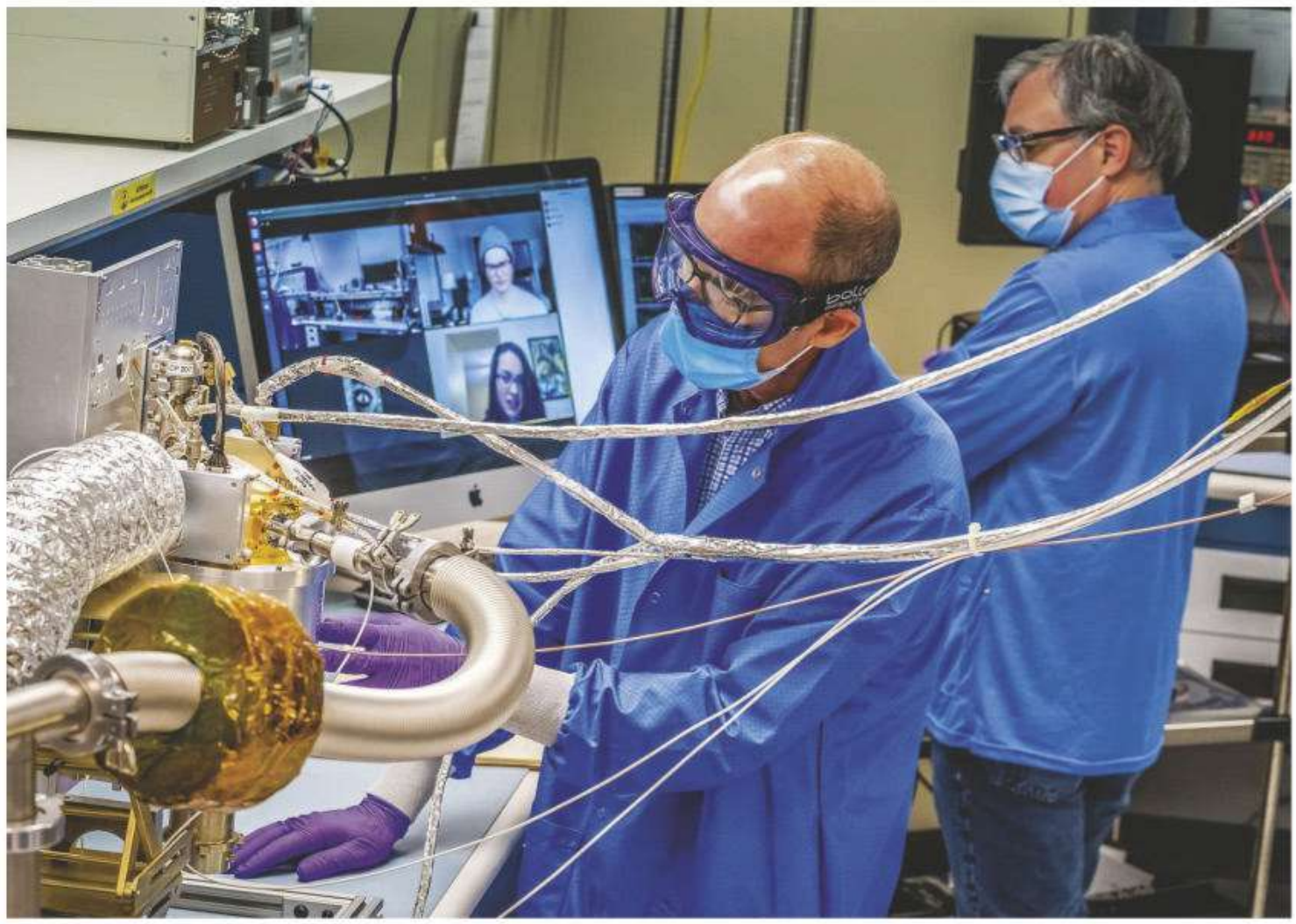
And that was the beginning of the mission. Elkins-Tanton became the principal investigator and is currently in the final phases of shepherding the mission to its launch, in August 2022.

LIKE NOTHING WE'VE SEEN BEFORE

The mission is equipped with a suite of science instruments. There's a multispectral imager that will provide high-resolution images at a variety of wavelengths. This will allow the team to identify and distinguish areas of exposed metal and rock on Psyche's surface. Since no one has even seen an asteroid of this type before, no one knows how it'll appear.

"I can't wait to see what the surface of Psyche looks like. It could be really quite unusual and strange. I'm hoping that it'll look totally bizarre," says Elkins-Tanton.

The images could show large provinces of exposed metal. In which case, the craters that cover other asteroids could look odd here, because impacts happen differently



"Psyche is gonna surprise us and show us that it's something totally different altogether"

in metal to rock. "We'd expect to see some quite strange shapes," says Elkins-Tanton.

The pulverised rock, known as regolith, created in such impacts could also be missing at Psyche as it's not clear whether metal can form a regolith. It all makes predicting what the asteroid will look like very difficult.

There's also a gamma ray and neutron spectrometer that will measure the chemical elements on Psyche's surface, giving us an estimate of its overall composition. This is the data that de Leon is most excited about because while the multispectral imager will identify areas of rocks and metal, the spectrometer will give the composition of the metal and reveal what has happened to it. "Only the chemical analysis can tell you this information," she says.

Then there's the magnetometer, which will detect whether Psyche has a magnetic field – crucial for understanding its past. The reason is that a molten iron core acts like a dynamo and generates a magnetic field. This is happening beneath our feet in Earth's core even now.

ABOVE LEFT The Psyche spacecraft's high-gain antenna undergoing testing in late 2020

ABOVE Engineers at Johns Hopkins Applied Physics Laboratory in Maryland, USA work on the Psyche spacecraft's gamma ray and neutron spectrometer

As a core radiates away its energy and solidifies, parts of the resulting solid iron mass will retain an imprint of that magnetic field. "If we find that strong magnetic field at Psyche, then we'll know right away that it was a part of core and then we can build upon that. So that would be a beautiful thing to find out right away," says Elkins-Tanton.

They've certainly got their work cut out. Not only must they investigate the origin of Psyche, and try to explain the missing mantle problem, there's also a family of meteorites that could have come from the same parent body as Psyche. They're called the CB chondrites and they display a very high percentage of metal surrounding round droplets of rock. One idea is that they are 'splashes' from the same collisions that unearthed Psyche.

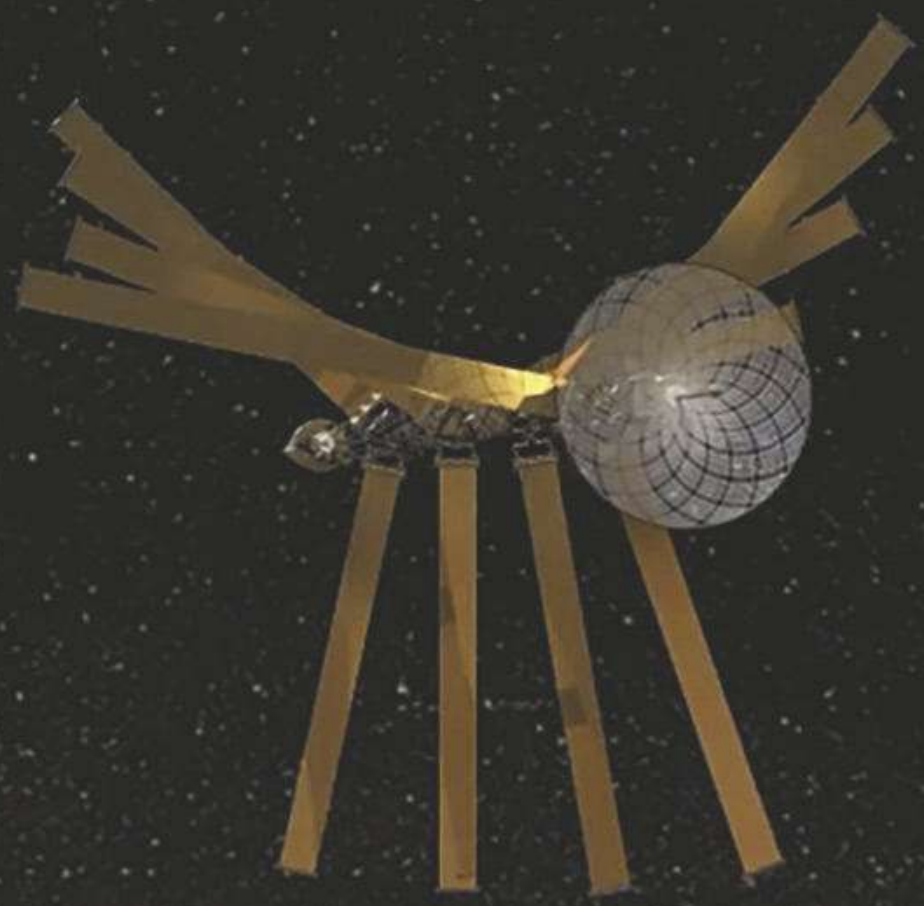
It's an incredible thought that missions like Psyche are putting us in a position to examine the asteroid belt with such precision that, not only will we understand the general process of planet formation, but we'll also be able to link different bodies to specific events and each other.

The other incredible thought about this mission is to prepare for the unexpected. As Elkins-Tanton says, "The thing that I'll add here, which I always add, is that almost certainly everything I'm telling you right now is wrong. And that Psyche is gonna surprise us and show us that it's something totally different altogether."

And when all is said and done, that is perhaps the most beautiful thing about science. **SF**

by **DR STUART CLARK** *(@DrStuClark)*

Stuart is an astrophysicist and a Fellow of the Royal Astronomical Society. His latest book Beneath The Night *(£14.99, Guardian Faber) is out now.*



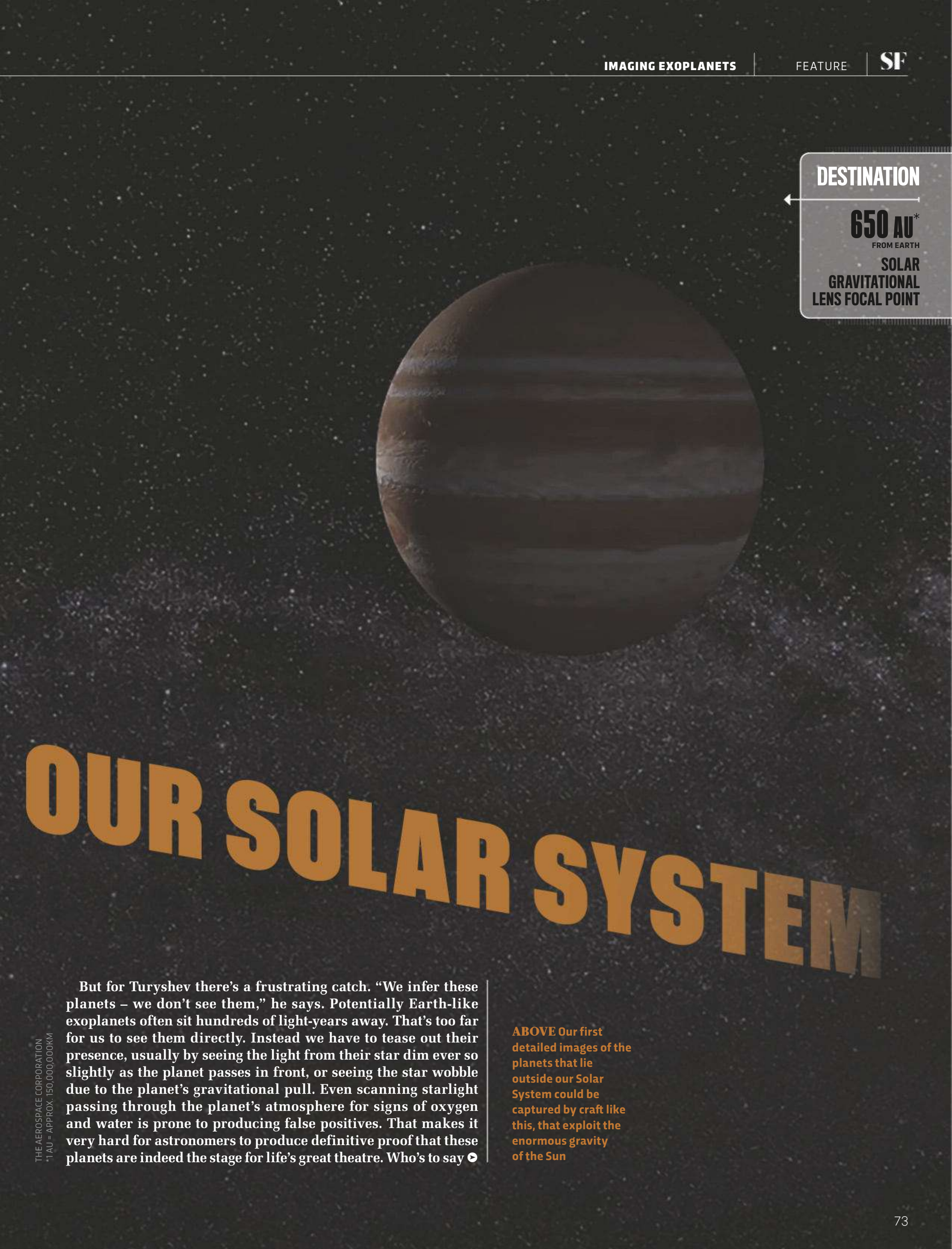
HOW TO SEE BEYOND

Astronomers generally view the Sun as an obstacle to the objects they want to study. But it might just be the key that enables them to observe Earth-like exoplanets located many light-years away

WORDS COLIN STUART

A spacecraft hurtles out of the Solar System travelling faster than any rocket, probe or instrument we've launched into space before. It's on a daring mission to answer some of the most fundamental questions about the Universe once and for all. "We've all been asking them since we were six years old," says Slava Turyshev from NASA's Jet Propulsion Laboratory. "Are there other planets? Can we see them? Is there life?"

Astronomers have revolutionised our understanding of our place in the Universe over the last quarter of a century. In 1995 they found their first alien planet orbiting a Sun-like star. It whetted their appetites to such a degree that we've been hunting them down ever since. At the last count there are over 4,000 of these exoplanets in our databases. Some of them even appear to have similar traits to Earth – close in both size and temperature. That quickens the pulse and often makes headlines because if life can thrive on our planet, it could be doing the same on an exoplanetary cousin.



OUR SOLAR SYSTEM

But for Turyshev there's a frustrating catch. "We infer these planets – we don't see them," he says. Potentially Earth-like exoplanets often sit hundreds of light-years away. That's too far for us to see them directly. Instead we have to tease out their presence, usually by seeing the light from their star dim ever so slightly as the planet passes in front, or seeing the star wobble due to the planet's gravitational pull. Even scanning starlight passing through the planet's atmosphere for signs of oxygen and water is prone to producing false positives. That makes it very hard for astronomers to produce definitive proof that these planets are indeed the stage for life's great theatre. Who's to say ▶

ABOVE Our first detailed images of the planets that lie outside our Solar System could be captured by craft like this, that exploit the enormous gravity of the Sun

THE AEROSPACE CORPORATION
*1 AU = APPROX. 150,000,000KM

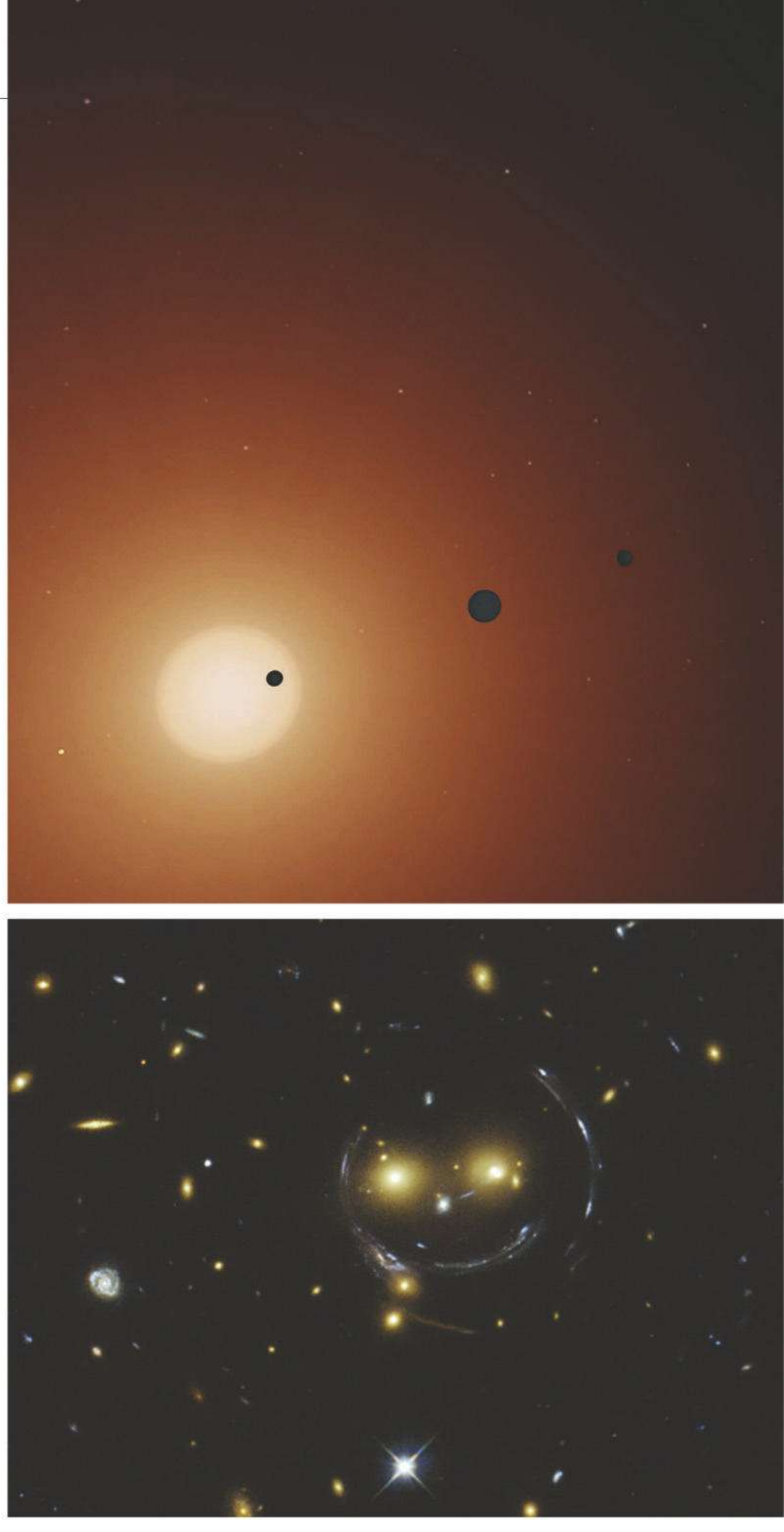
they aren't just lifeless mirages in the cosmic desert? It's no wonder we're aching for a closer look.

SIZE MATTERS

The challenge of imaging an Earth-like exoplanet – even as just a single pixel in a photograph – is immense. "If I want to see another Earth from a distance of 100 light-years, I need a telescope with a diameter of 90km," Turyshev says. Its mirror would cover an area larger than London, Paris, New York and Tokyo combined. The biggest telescopes on Earth right now have mirrors around 10m across. Even the new Extremely Large Telescope, currently under construction in Chile, will 'only' have a 39m mirror when its finished in 2025. "We can't see the planets behind the headlines with existing telescopes or even those planned for the near future," Turyshev says. If we want a more detailed image – the kind that would tell us something useful about the planet – the diameter would need to increase even further.

All is not lost, however. Turyshev is the brains behind an audacious idea to exploit an astronomical loophole – something he describes as "a gift from nature". He's working on a brand-new way to image an Earth-like exoplanet using the biggest thing for light-years around: the Sun.

Massive objects like the Sun distort the fabric of space around them. The Earth, for example, is caught in the gravity well the Sun makes, which is why we're stuck in orbit around it. Any light approaching the Solar System from elsewhere is forced to follow this local curvature of space. The light ends up being bent around the Sun in an effect called gravitational lensing. Like a giant magnifying glass, the Sun amplifies the light from distant exoplanets by up to 100 billion times. To see an image of the exoplanet we just have to get a spacecraft to the region where the Sun brings its light to a focus. It's the Universe's own enormous telescope – one that astronomers could only ever dream of building. The Sun does so much of the heavy lifting that the spacecraft we send to catch the light would only need a one-metre mirror – less than half the diameter of the mirror in the Hubble Space Telescope.



NASA/JPL-CALTECH X2

ABOVE Five of the seven planets in the TRAPPIST-1 system are believed to be approximately Earth-sized

LEFT The Hubble Space Telescope spotted this distinctive Einstein ring in 2015, created by the gravitational lensing caused by the galaxy cluster SDSS J1038+4849 in the centre of the image

> **"Turyshev's working on a brand-new way to image an Earth-like exoplanet using the biggest thing for light-years around: the Sun"**

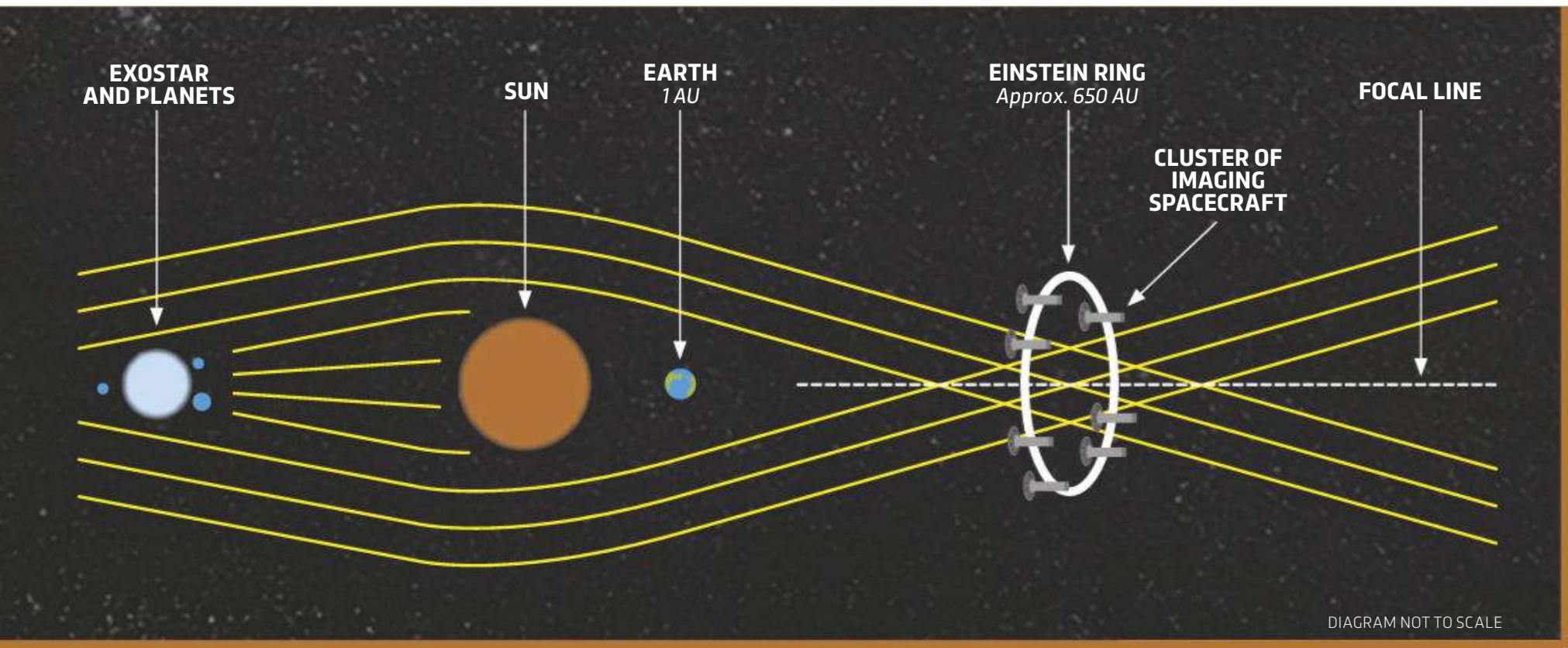
The potential for this kind of technique is huge. Rather than seeing the whole planet as a single pixel, Turyshev's calculations show that by using the Sun we could achieve a resolution of 20km per pixel. "We'd be able to see continents, oceans and weather patterns," he says. Forests and deserts would show up, too. A big city like London would take up more than one pixel. So we might be able to notice that regions change brightness as night falls and the lights of an alien city begin to shine. "With a solar gravitational lens that all becomes possible," Turyshev says.

We would be limited to only exploring one alien solar system per mission, though. "We won't be able to repoint towards a new star," Turyshev says. The precise alignment required means that the planet you want to image has to be in a direct line behind the Sun. Usually we head towards a planet we want to explore, but for this we'd need to travel away from it in the exactly the opposite direction. Probing another star system with the same spacecraft would require moving to another region of space, something beyond the scope of Turyshev's initial proposal. We would, however, be able to explore multiple planets orbiting the same star. The TRAPPIST-1 system could be a promising first candidate. We already know that there are seven roughly Earth-sized planets there and we could image them one by one as part of the same mission. Each planetary portrait would take around eight months to put together.

SAIL AWAY

With such a big prospective pay-off, you may be wondering why this hasn't been tried already. The reason is that it's an enormous engineering challenge. The solar gravitational lens brings the light of a typical exoplanet to an observable focus around 650 astronomical units (AU) away, where one AU is the distance between the Sun and Earth. For context, Neptune, the furthest confirmed planet in our Solar System, orbits the Sun at an average distance of 30AU. The Voyager 1 probe, the spacecraft that's travelled furthest from Earth to date, has only reached a distance of 150AU since its launch in 1977. NASA's New Horizons probe holds the record for the fastest spacecraft to depart from Earth, but was still only travelling at a rate of just over 3AU per year en-route to Pluto. At similar speeds it would take almost 200 years to trek out to the focus of the lens.

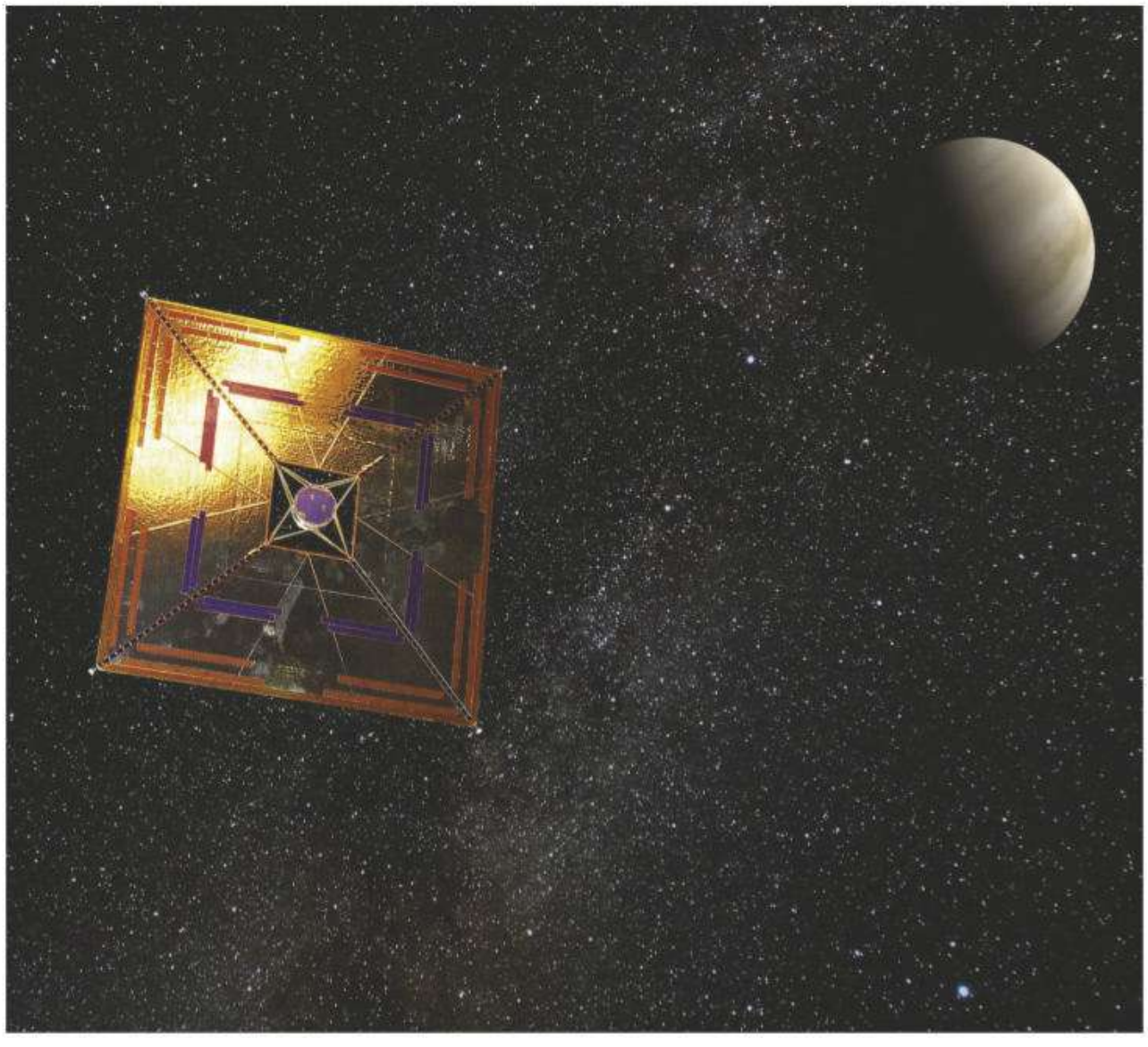
"We need to be able to get there in a human lifetime," Turyshev says. Not least because it's only fair that the people who build the spacecraft get to see the fruits of their labour. Everyone's inner six-year-old is also impatient – we want answers to those enduring childhood questions as soon as possible. To pull this off we're going to have to move away from the kind of propulsion we usually use for interplanetary missions. Instead a spacecraft equipped with a solar sail could reach speeds of ➤



HOW A SOLAR GRAVITATIONAL LENS WORKS

Light from exoplanets orbiting stars outside our Solar System is warped by the Sun's gravity. That light converges into a halo-shaped focal point known as an Einstein ring. By sending imaging spacecraft to that point, we could capture some of that light, which will have been sufficiently magnified by the Sun's lensing effect to allow us to discern details on those exoplanets.

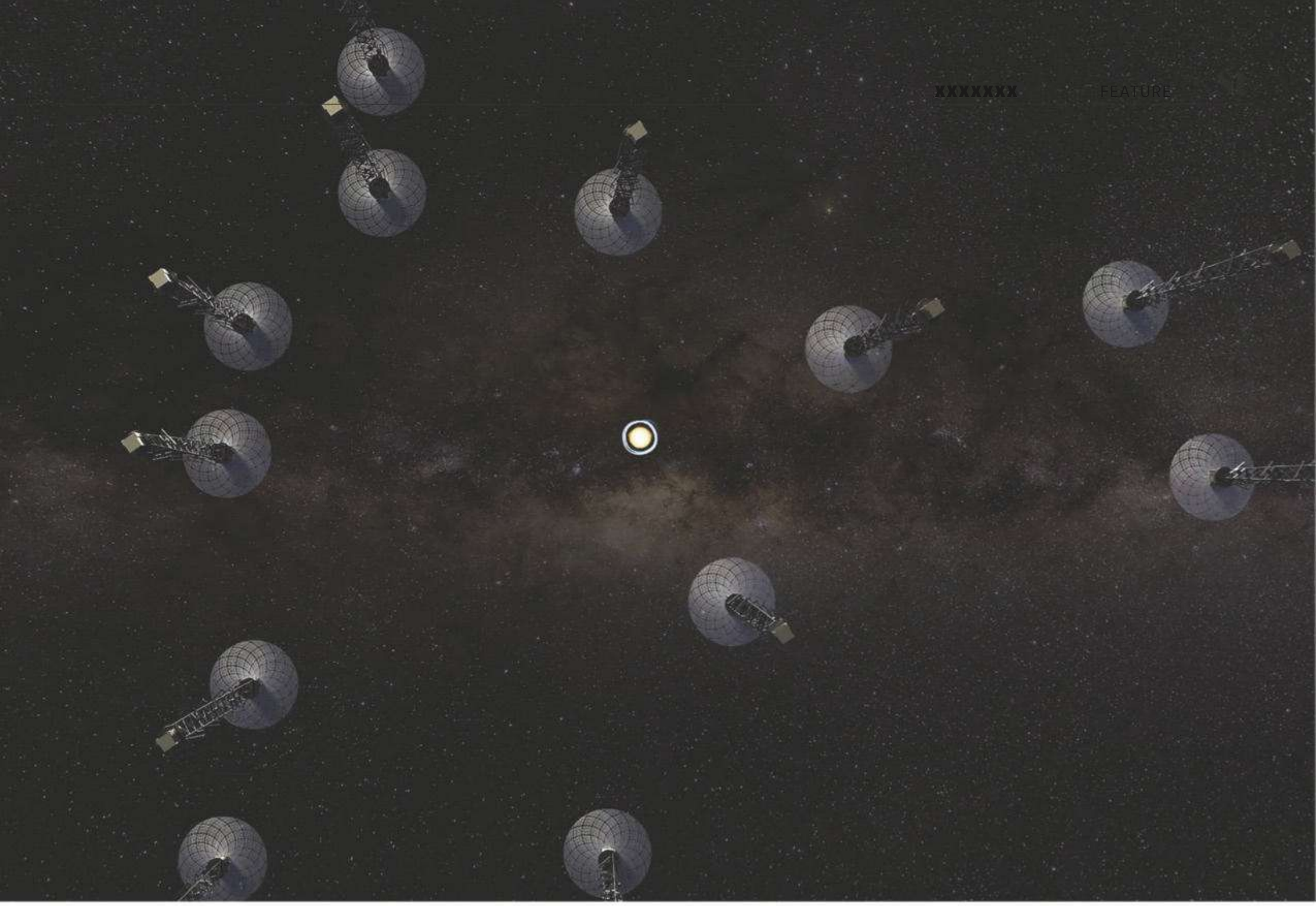
RIGHT Light captured by the imaging spacecraft could be combined to produce an image of an exoplanet like this



25AU per year, getting us there in around a quarter of a century.

Solar sails operate in a similar way to the sails on a boat, catching the gusts of solar wind blown out by the Sun or riding on the jet stream of light – particles of sunlight hitting the sails propel the craft just like particles of air do on Earth. "Missions like Japan's IKAROS and [The Planetary Society's] LightSail have already successfully demonstrated solar sails in space," Turyshev says. "We already have the technology we need to do this." His proposed spacecraft would be equipped with 16 sails, each with an area of 1,000m^2. NASA is keen enough on the idea to back his work with funding through its Innovative Advanced Concepts programme.

Prof Lewis Dartnell, an astrobiologist at the University of Westminster, is excited by the prospect. "If we could build such a



THE AEROSPACE CORPORATION X2, SLAVA TURYSHEV, ANDRZEJ MIRECKI/WIKIPEDIA

futuristic technology it would be an absolute boon for astrobiology," he says. "This would give astronomers an enormous capability for assessing how habitable the exoplanet might be."

Dr Nicholas Rattenbury, from the University of Auckland in New Zealand, agrees. "To discover features on an exoworld that we could associate with a biosphere would be sensational," he says. Although his enthusiasm is tempered with a note of caution. "This would be an extremely challenging mission – it represents one of the most ambitious goals I've seen in exoplanet discovery."

IS ANYONE LOOKING BACK?

So what's the next step on the road to making such a complex dream a reality? Turyshev is planning to fly a technology demonstration mission – a scaled-down version to show that the solar sail propulsion system could work in principle. "It would reach speeds of 7AU per year – twice the current record," he says. If that goes well, he hopes we could launch the spacecraft for real by 2035, meaning it would arrive at the focus of the solar gravitational lens in around 2060. "It's an aggressive timeline, but we already have all the ingredients in place – we just have to put them together," he says.

We may have to wait a while, but patience is part of the process. "The hunt for another Earth is a generations-long search," says Prof Sara Seager, an exoplanet hunter at the Massachusetts Institute of Technology. But we still need to be thinking about tomorrow's telescopes today. "We 100 per cent want to invest in brand-new technologies – [they're] needed if we want follow up on any intriguing discoveries we make in this generation," she says. All the more reason to continue to catalogue intriguing systems such as TRAPPIST-1 so that we're ready to go when new missions come online later this century.

Coincidentally, Turyshev's proposed timeline would see the first image returned not long after the centenary of the launch of Sputnik 1, the first satellite to reach Earth orbit. If it takes us a mere 100 years to go from dipping our toe in the celestial waters to photographing sprawling metropolises on alien planets, could there be other civilisations using their own solar gravitational lens to peer at Earth? "Absolutely," says Turyshev. "I've no doubt that somewhere else in the Galaxy there are people who know how we live here."

Thanks to his work, it may only be a matter of time until we join a club of astronomers whose membership extends beyond the Solar System and we can finally get answers to those questions that our inner children won't stop asking. **SF**

ABOVE Light from stars outside the Solar System would be warped by the Sun's gravity, possibly appearing as a halo-like 'Einstein ring' on the opposite side, and could be collected by imaging spacecraft

FAR LEFT The Japanese IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) spacecraft was the first to successfully use solar sails

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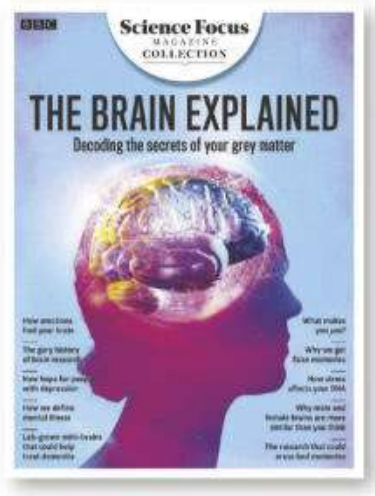

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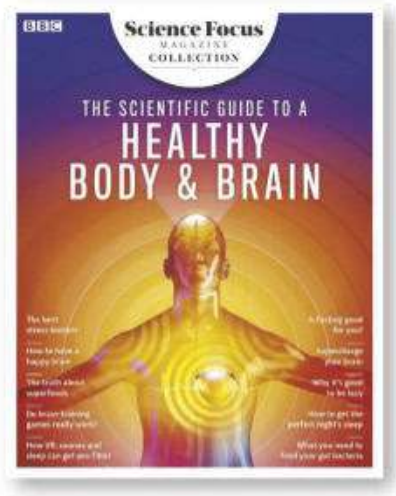

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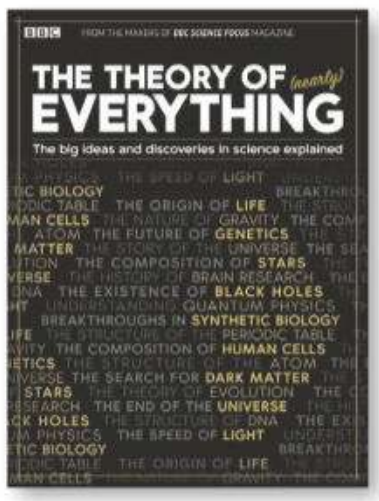

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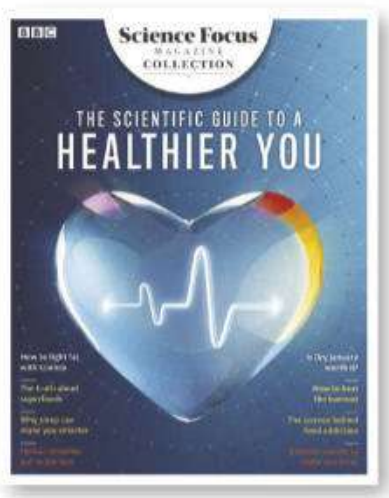

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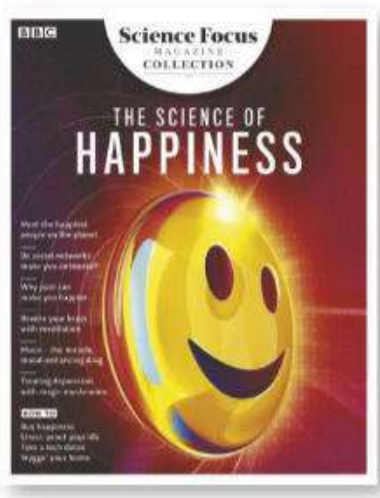

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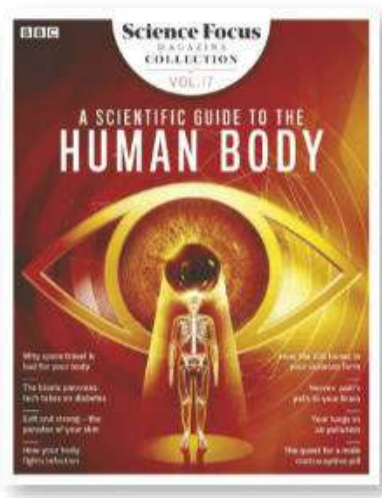

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Q&A

YOUR QUESTIONS ANSWERED

... COULD DINOSAURS HAVE CAUGHT COVID-19?
... DO WOMEN'S PERIODS REALLY SYNC UP?
... DO THE SUN'S RAYS GET FURTHER APART FROM EACH OTHER AS THEY REACH EARTH?
... WHY DOESN'T GLUE STICK TO THE INSIDE OF THE BOTTLE?
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... WHY DO WE HAVE TOENAILS?
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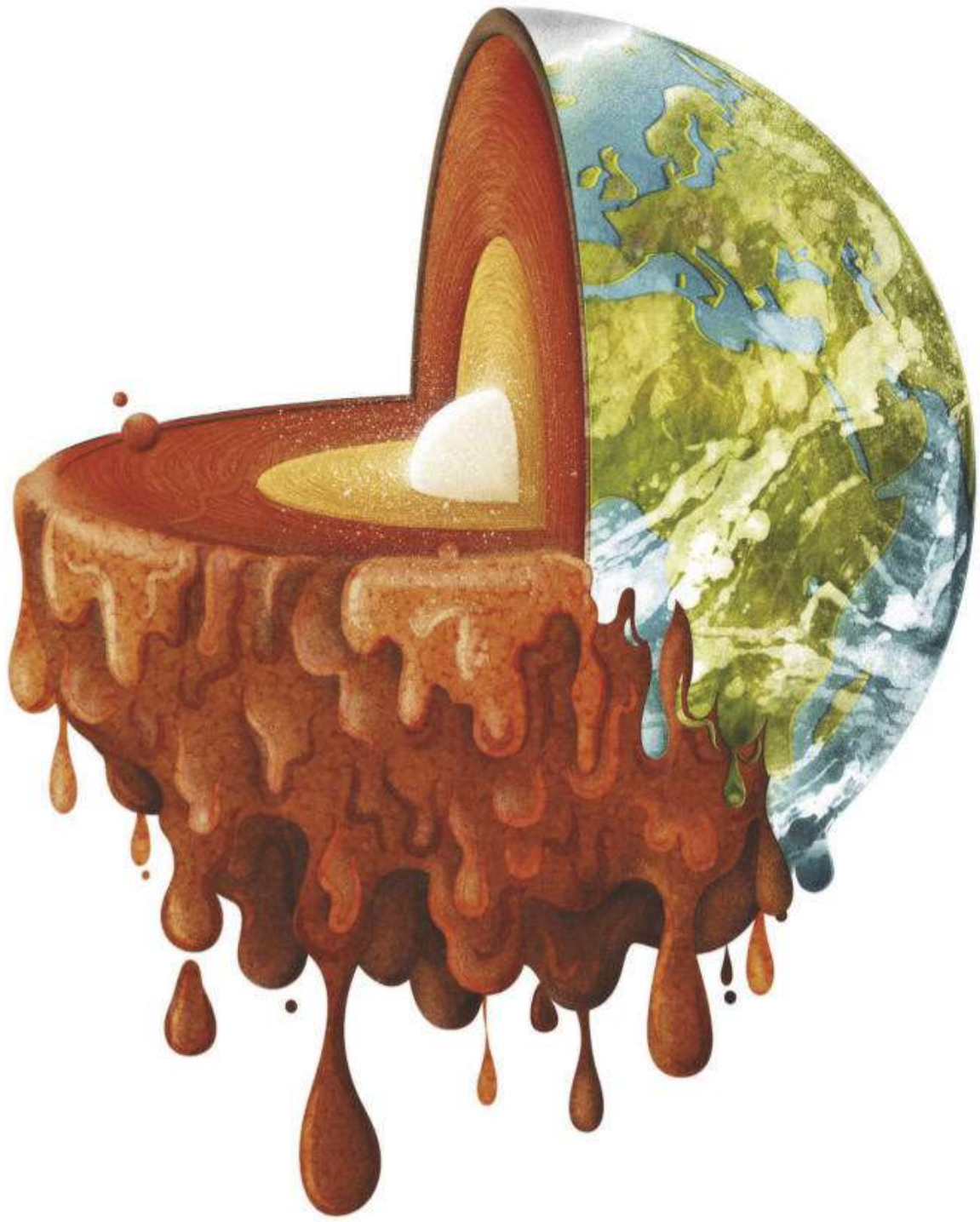


ILLUSTRATION: DANIEL BRIGHT

DANIEL JEFFREY, NORFOLK

IF EARTH'S CORE IS AS HOT AS THE SUN, WHY DOESN'T EARTH MELT?

Although we haven't been there, there's a lot we know about Earth's core. From the study of seismology – measurements of sound waves travelling through Earth (in some cases from nuclear test explosions) – we can tell that the core is molten. Plus, from our knowledge of the abundance of elements in the Universe and how they behave, we think it's made mainly of iron under huge amounts of pressure.

All this indicates its temperature is about 6,000°C, similar to the temperature of the Sun's surface. And Earth's core is only 3,000km from its surface – if the Sun were as close as that, it would melt us entirely.

So why doesn't Earth's core fry us all? For a start, the core is surrounded by a mostly solid mantle of rock. The crust we live on floats on that mantle, giving us more protection than empty space would. But the most important reason we don't all melt is the difference between heat and temperature. Roughly speaking, heat is energy and temperature is density of energy, basically how much energy is crammed into a given size.

A spark from a sparkler can have a temperature of 1,500°C, but won't really hurt you. On the other hand, a bath of boiling water at only 100°C would kill you. That's because the bath contains much more heat energy. To melt the whole Earth, you would need much more energy than the heat in its core. The Sun is huge and could easily do that, of course... but luckily it's 150,000,000km away. ***JB***

TOP TEN

COUNTRIES WITH SPEEDIEST INTERNET

A public service announcement to all gamers: don't move to Yemen. With an average broadband speed of 0.58Mbps (over 106 times slower than the net aboard the International Space Station), it would take just under three days to download the likes of *Red Dead Redemption 2*. But which country has the fastest net? (Spoiler: with an average speed of 37.82 Mbps, it's not the UK, which comes in at 47th).

1. Liechtenstein — **229.98**Mbps

Fast enough to download **S Club 7's greatest hits album, *Best*** in 0.05 seconds

2. Jersey — **218.37**Mbps

Fast enough to download the **2014 film *The Jersey Boys*** in 10.4 seconds

3. Andorra — **213.41**Mbps

Fast enough to download **the 4K extended edition of *The Lord Of The Rings* trilogy** in 130 seconds

4. Gibraltar — **183.09**Mbps

Fast enough to download ***Speed*, starring Keanu Reeves** in 26 seconds

5. Luxembourg — **118.05**Mbps

Fast enough to download **the entire *Fast & Furious* movie franchise** in 154 seconds

6. Iceland — **116.88**Mbps

Fast enough to download **all the Harry Potter books** in 12 seconds

7. Switzerland — **110.45**Mbps

Fast enough to download ***Top Gun*** in 41 seconds

8. Hong Kong — **105.32**Mbps

Fast enough to download **Barry White's *Greatest Hits* album** in 0.38 seconds

9. Monaco — **104.98**Mbps

Fast enough to download ***The Sims*** in 142 seconds

10. Hungary — **99.74**Mbps

Fast enough to download ***Days Of Thunder*** in 43 seconds

SOURCE: *Worldwide broadband speed league*

NATURE'S WEIRDEST

CHRISTIAN JONES, LLANELLI

COULD DINOSAURS HAVE CAUGHT COVID-19?

We can't know for sure if a dinosaur could be infected with COVID-19, but studies of coronavirus genomes indicate that they originated after the dinosaurs went extinct. There is evidence that dinosaurs were affected by other diseases, however.

Palaeontologists have identified many 'palaeopathologies' on dinosaur bones, which indicate various maladies including bone cancer, gout, a bone infection called osteomyelitis and infestation from parasites. In one famous case, the *Tyrannosaurus rex* skeleton nicknamed 'Sue' was found to have many holes in its lower jawbone. The holes are similar to injuries seen in modern-day birds infected with a parasite called *Trichomonas*, which makes it difficult to swallow and breathe. ***SB***

CREATURES...

THE TARSIER

Never feed a tarsier after midnight. Hang on... that's a gremlin. But it's an easy mistake to make. With their oversized eyes, protruding ears and furry bodies, they're dead ringers for the 1980s mischief makers.

With bodies rarely above 15cm long, tarsiers are one of the world's smallest primates, found in the forests of Malaysia, Indonesia, Brunei and the Philippines. These largely solitary animals are the world's only entirely carnivorous primate; consuming a diet of insects, reptiles and birds, which they hunt at night.

Their enormous eyes, which are densely lined with photoreceptive cells called rods, are specialised for seeing in dim light. If humans had similarly proportioned peepers, they'd be the size of grapefruits. Tarsier eyes are so big that they can't rotate in their sockets, so the animal has developed the ability to swivel its head almost 180° in either direction to look around – think Baby Yoda meets *The Exorcist*.

Their large ears can detect the high frequencies emitted by their prey and the structures also swivel, giving the tarsier excellent directional hearing. Their fingers are tipped with swollen pads, which helps them grip trees, and their long, springy legs allow them to leap distances of up to five metres. If humans had similarly proportioned legs, we'd be able to leap over five double decker buses, but please don't try this at home. *HP*

DEAR DOCTOR...

HEALTH QUESTIONS DEALT WITH BY *SCIENCE FOCUS* EXPERTS

DO WOMEN'S PERIODS REALLY SYNC UP?

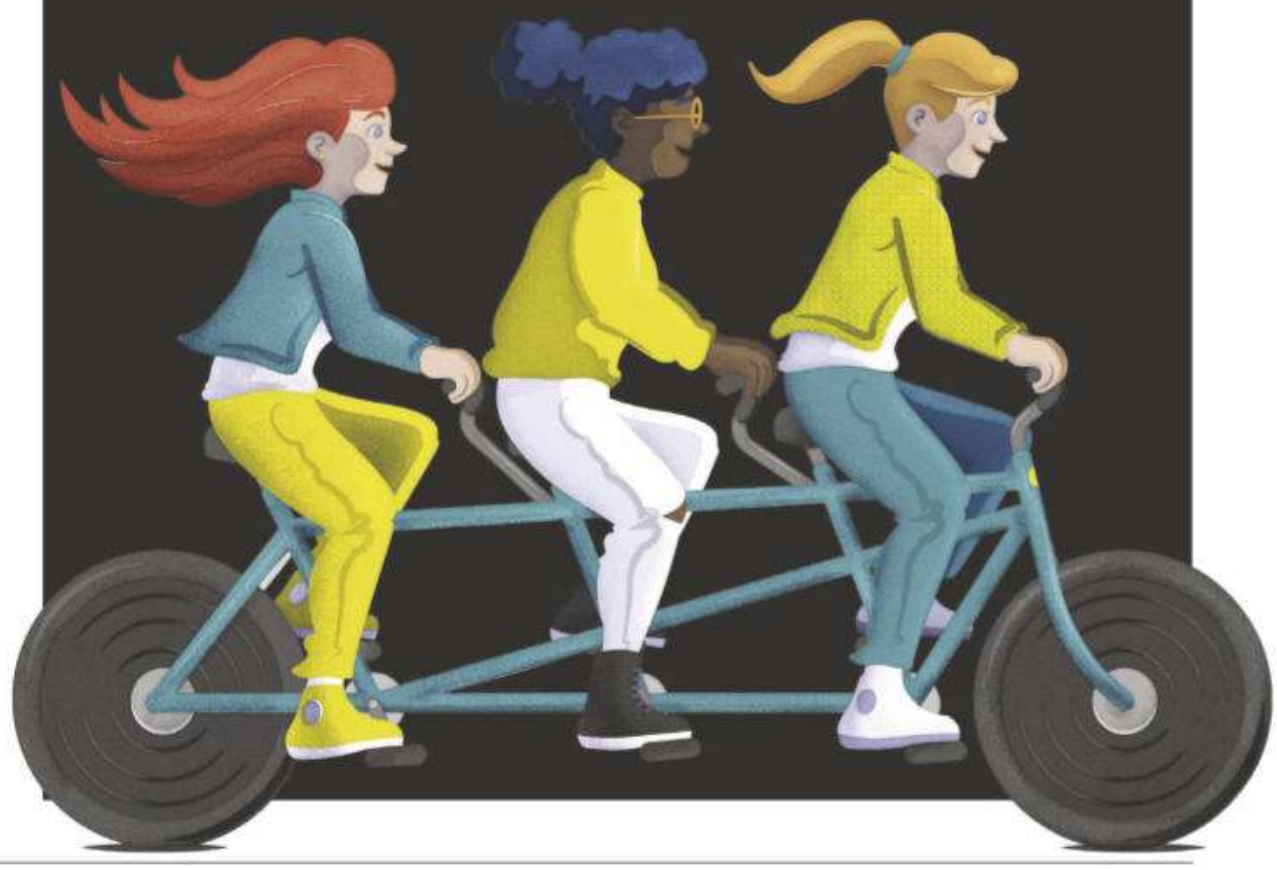
It's long been speculated that women's periods can sync when they spend time together. Some women swear by it and an interaction of pheromones (chemicals that affect behaviour) is usually offered as an explanation.

The idea has been around since a researcher called Martha McClintock studied the cycles of 135 American students in 1971 and claimed that the onset of menstruation was more similar among roommates than random pairings of women.

A popular evolutionary explanation emerged that this phenomenon helps females avoid being monopolised by a dominant male, because the women are fertile simultaneously. At a time when feminism was gaining traction, the idea that females would cooperate in the face of male domination was persuasive. But more than 30 years of investigation have passed since McClintock's research and multiple studies since have failed to provide evidence for this phenomenon. Others have also pointed out methodological oversights in the original study.

Of course, period synchronisation is a tricky topic to examine. As women's cycle lengths vary so much, we don't know if pheromones can influence menstruation. Plus, any study should expect some women's cycles to overlap by random chance.

The theory of menstrual synchrony is likely to stick around though. After all, the thought of sharing periods with someone may make you feel closer to them and less stigmatised – not to mention making three-for-two tampon offers all the more tempting. *NM*



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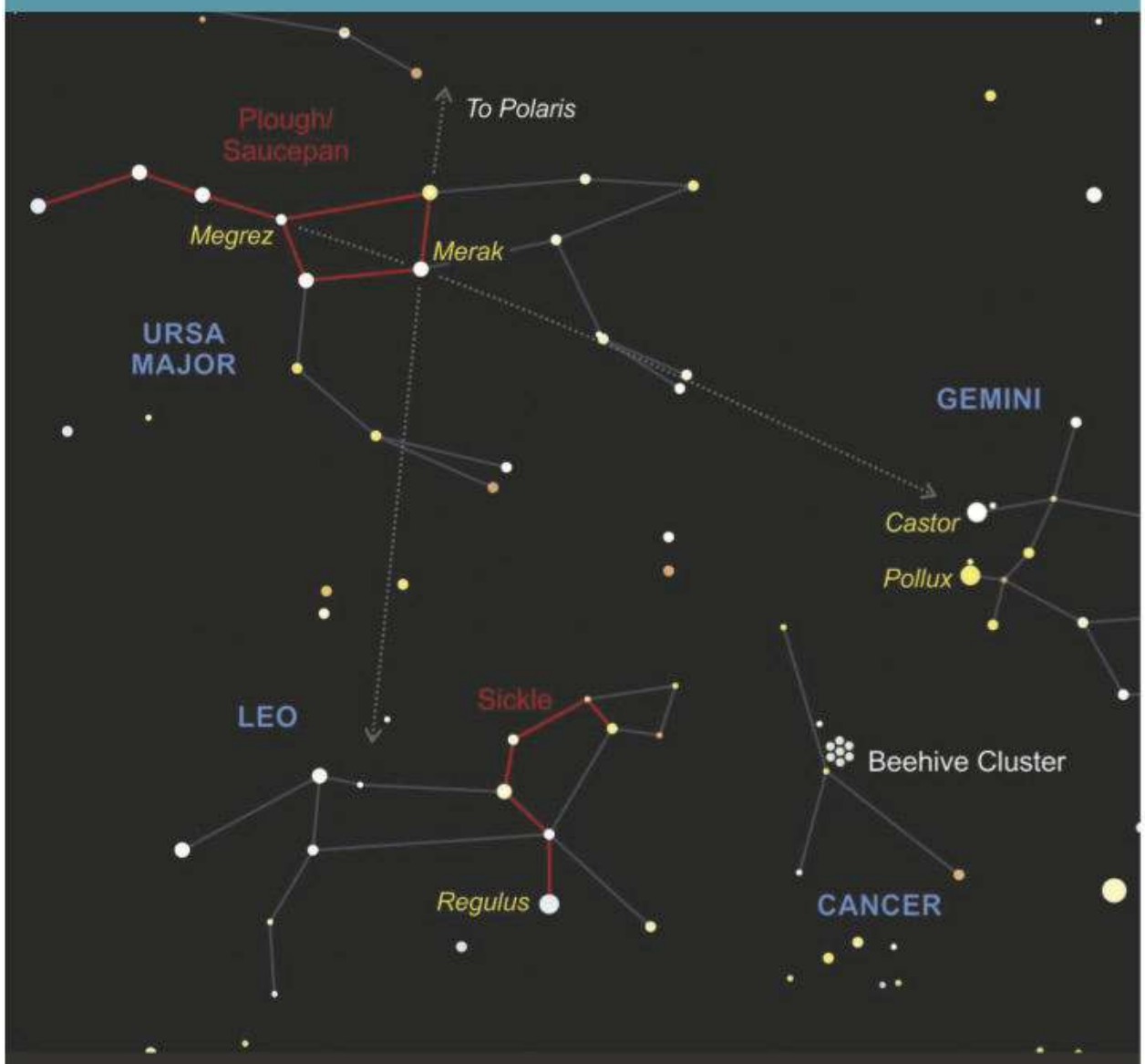
ASTRONOMY FOR BEGINNERS



HOW TO SPOT THE BEEHIVE CLUSTER

WHEN: MARCH-APRIL

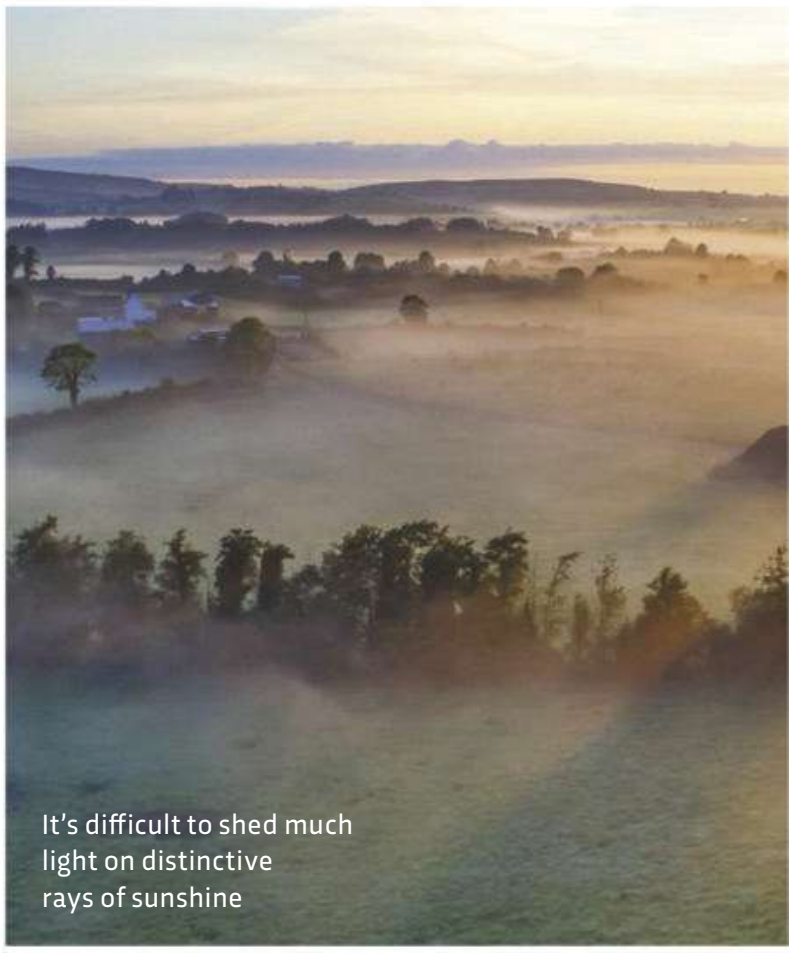
One of the best things to find in early spring, if you have a pair of binoculars, is the Beehive Cluster. Like the Pleiades, the Beehive is an open star cluster, a group of a few thousand relatively young stars (many of them are only 600 million years old, compared to our Sun's 4.5 billion). These stars are found in the same place because they all developed out of the same huge cloud of gas.

At 520-610 light-years away, it's one of the nearest open clusters to Earth and has more bright stars than most of the other close clusters, such as the Alpha Persei cluster. It can be seen very faintly with the naked eye in dark skies, but is much more visible with binoculars. Overall, it stretches more than three times the Moon's diameter across the night sky.

The Beehive Cluster is in the constellation of Cancer. To find Cancer, it's best to first look for the pair of stars Castor and Pollux, in the neighbouring constellation Gemini. You can start at the Plough (also called the Big Dipper) to find them. If you imagine the Plough is a pan with a handle, draw an imaginary line from the end of the handle through the star that makes the top edge of the pan, called Merak. Keep this line going and you'll see a pair of bright stars. These are Castor and Pollux.

Then, you have to find Leo, which is distinctive because of its question mark-shaped asterism. There are two pointer stars in the Plough – the two outer stars in the bowl – that can be used to find Polaris (or the North Star), which will appear very bright. Draw a line in the opposite direction and you'll get to Leo.

Looking halfway between Gemini and Leo, you'll find Cancer, with the Beehive Cluster in the middle of the constellation. ***AB***



It's difficult to shed much light on distinctive rays of sunshine

MICHAEL POTTS, SUNDERLAND

WHY DOESN'T GLUE STICK TO THE INSIDE OF THE BOTTLE?

It depends on the glue type, but a lack of air inside the bottle is key. PVA glue contains long molecules, called polymers, and water. When you squeeze the glue out, the water evaporates to the air, leaving just sticky polymers. Super glue, on the other hand, contains a chemical that hardens as soon as it hits water vapour in the atmosphere.

In short, PVA glue doesn't stick to its bottle because water is trapped inside while super glue's container keeps water out. ***ED***

JEFF SLEE

DO THE SUN'S RAYS GET FURTHER APART FROM EACH OTHER AS THEY REACH EARTH?

Ah... if by the Sun's rays you mean the photons it emits then, due to their quantum nature, it isn't actually possible to define their location (nor the distance between them) in a traditional sense. Furthermore, because photons are 'bosons', they can't even be regarded as having separate identities. However, scientifically, what we can do is talk about the intensity of sunlight at the Sun's surface compared to its intensity at Earth (which is lesser by a factor of about 46,000). ***AG***

CROWDSCIENCE

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Tune in every Friday evening on BBC World Service, or catch up online at **bbcworldservice.com/crowdscience**

WHY DOES IT FEEL SO GOOD TO SWEAR?

If you've ever banged your toe and then yelled an expletive, you'll already know part of the reason for swearing's appeal – it helps us cope with pain. Psychologists have actually tested this under controlled conditions in the lab. When volunteers swore repeatedly while plunging their hand in icy water, they were able keep it there for longer compared to other volunteers who tried the challenge in silence or while uttering a non-swear word.

One theory is that swearing has this effect because it triggers an emotional reaction in the brain and body. Consistent with this, swearing raises your heart rate and increases your sweat levels, both of which are signs of your body shifting into a survival 'fight or flight' mode.

Other findings hint at the unique way that our brains process swear words. For instance, people with brain damage affecting their ability to speak (known as aphasia) will sometimes have preserved the ability to swear. A related finding is that swearing can even boost your strength, perhaps because it makes the effort easier; in another study, volunteers displayed stronger handgrip strength when they swore during the test.

So, swearing boosts our pain resistance and strength, but you might want to use this temporary superpower sparingly. More recent research has found that the pain-busting benefits of yelling naughty words is disappointingly diminished for people who swear lot in everyday life. ***CJ***

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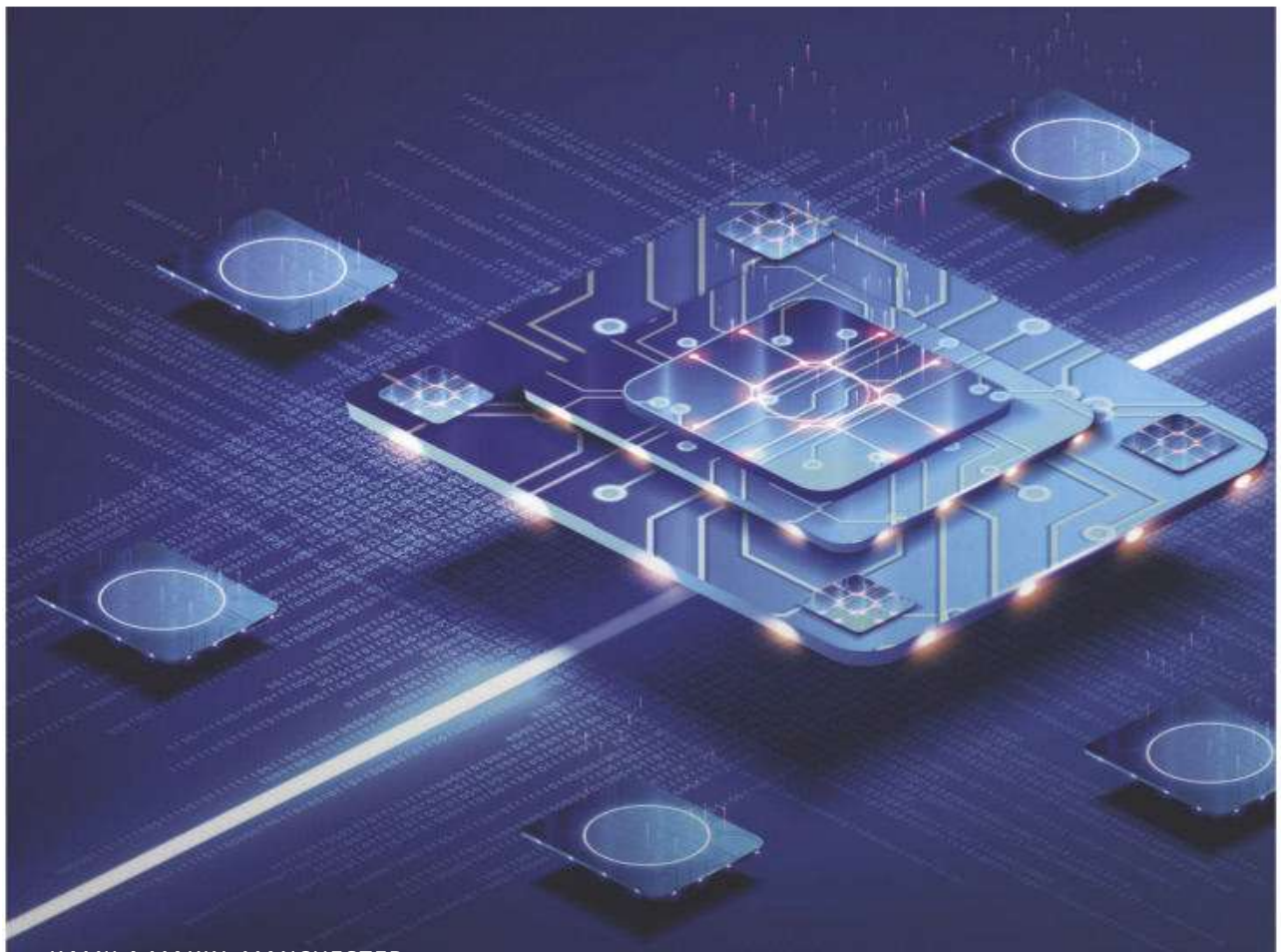


KAMILA MAKIN, MANCHESTER

HOW DIFFERENT IS A QUANTUM COMPUTER FROM MY LAPTOP?

Your laptop, like all conventional computers, manipulates electricity within its silicon chips. Tiny amounts of electrical current are turned on or off, representing logical signals true and false, or binary numbers one and zero. All conventional computer hardware is based on logical operations on binary digits (bits) for that reason.

However, quantum computers manipulate individual quantum elements such as electrons or photons, which in this context are called qubits.

It's the weird quantum properties of these tiny particles that give quantum computers their power. For instance, due to their 'spin', electrons may be up or down – and photons may be vertical or horizontal – at once. This 'quantum superposition' means that a qubit is in both states simultaneously. Well, that is until it interacts with some external factor that will then cause its state to become set – any vibration or disturbance nearby can cause these collapses. To prevent such quantum decoherence, scientists try to preserve the fragile superposition states of qubits in vacuum chambers and fridges colder than outer space. Qubits also rely on a weird property known as entanglement, where the property of one particle is entangled with another. This is where it gets really complicated. If we make two entangled particles with total spin of zero and the state of one particle collapses such that its spin is clockwise, the state of the other particle will be anticlockwise – even if the two particles are nowhere near each other.

All this basically means is that, once entangled, qubits can be used to represent huge numbers of possible numbers at the same time. For instance, Google's quantum computer Sycamore had 53 qubits, which can represent more than 10,000,000,000,000,000 (10 quadrillion) combinations simultaneously. This meant it could perform a calculation in 200 seconds that would take an ordinary computer 10,000 years.

In theory, this means that a quantum computer could perform specialised calculations that are out of reach of conventional computers (a concept called quantum advantage or supremacy). But due to the delicate storage conditions required, there's still a long way to go before we can have quantum processors in our laptops. ***PB***

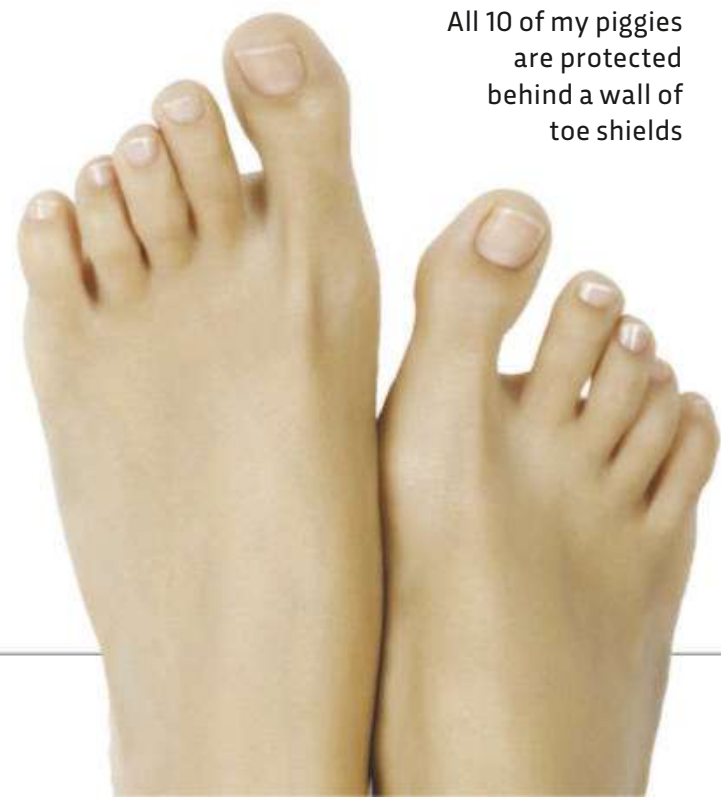
Ear loops will help ensure your mask(s) seal well on to your face

ANDY ORTON

WHY DO WE HAVE TOENAILS?

Nails are made of keratin, a protein found in hair, fur, claws and hooves. But unlike claws, nails are wide and flat, shielding the tips of fingers and toes from injury.

As well as protecting your delicate digits, fingernails provide a rigid backing to help you grab and separate small objects. Just imagine picking up a jigsaw piece or peeling a sticker from its backing – you'd struggle without nails. Monkeys and apes also use their feet for delicate tasks like these, and scientists believe nails evolved in primates to help with operations like removing ticks and grasping branches tightly. ***CA***



All 10 of my piggies are protected behind a wall of toe shields

MEGAN CLARKE, BATH

HOW MANY FACE MASKS SHOULD I WEAR TO PREVENT THE SPREAD OF COVID-19?

Face masks help stop the spread of COVID-19 in two ways. First, they disrupt the flow of air from your mouth and nose. If you're infected with COVID-19, but wear a mask, your virus-containing respiratory droplets won't spread as far.

Second, some face masks can also protect you from catching the virus. These masks filter the air you're breathing in, stopping virus-containing droplets before you inhale them. Not all face masks are good at this, however. Thin fabric face masks, especially ones that don't fit securely, aren't very effective at filtering the virus out. In contrast, properly-fitting, high-grade masks such as KN/N-95 or FFP-2/3 masks can be highly effective at stopping the virus.

If high-grade masks aren't available, the filtering capacity of fabric masks can be increased by layering multiple masks together (wearing a fabric mask over a surgical/medical mask). The additional layers of fabric help stop the virus, when you're inhaling and exhaling. It's not necessary to layer a cloth mask over a high-grade mask, as these are already very good at filtering out the virus.

It's also not recommended to layer more than two fabric masks, as this could make it more difficult to maintain proper fit and placement of the masks. For masks to work best, they need to seal around your face, so that the air you're breathing is filtered by the mask. High-grade masks are designed to form a good seal. If you're wearing fabric masks, however, your protection can be increased by knotting the ear loops to minimise any gaps and ensure a closer fit. ***JR***

QUESTION OF THE MONTH

ROB SEDGWICK, DORKING

DO ANIMALS HAVE ACCENTS?

Some animal communication is entirely hardwired. A moth can't learn to produce a different mating pheromone, for example. But animals with more complex communication often learn the subtleties of their language by copying those around them.

In 1958, researchers at Cambridge University showed that male chaffinch birds reared in isolation would grow up to sing a much simpler song; all the trills and flourishes are apparently learned from other chaffinches. Over time, isolated populations within the same species develop their own regional songs.

A 2016 study at Prague University found that yellowhammers introduced to New Zealand from England in the 19th Century were using songs no longer sung by native yellowhammers back home.

An accent is more subtle than a whole new song though. The varying repertoire of songbird populations is more akin to different dialects. The message is basically the same – "Single male finch, non-smoker, GSOH, seeks mate" – but the expression is different. Whales and dolphins use different sequences of clicks in their songs from one group to another, but here the purpose is to signal membership, not attract mates. This makes whale songs more like national anthems or football chants than accents. To qualify as an accent, we'd need to find an animal that produces a regionally distinct vocalisation, which can still be understood by other groups, even if they hadn't encountered it before.

In 2006, it was reported that cows from different counties might moo with distinct accents, but this was actually a PR stunt for a West Country cheese manufacturer. However, a 2012 study at the University of London found that when young goats joined a new social group, their bleats adapted to match those of the other goats. Yet, findings like this are extremely rare. ***LV***

"Awlwite me ol' China. Put yer plates up and I'll get a cuppa Rosy on"

WINNER

Rob wins a **Let's Explore Oceans mega pack**, worth £69.99. It comes with a set of VR/AR goggles, powered by your smartphone, to take you on an immersive journey through the sea. Learn about the anatomy of great whites and humpback whales, before practising your underwater photography skills. Readers can receive a 20 per cent discount on the Let's Explore Oceans mega pack – use the code VRoceans2021. **letsexplore.com**

EMAIL YOUR QUESTIONS TO **QUESTIONS@SCIENCEFOCUS.COM**

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THE EXPLAINER

WILL ARTIFICIAL MEAT CHANGE THE WORLD?

HOW IS ARTIFICIAL MEAT MADE?

Also known as cultured or cell-based meat, artificial meat is grown from animal cells in a laboratory. Start-up companies have grown artificial beef, pork, chicken and even fish. However, none is commercially available yet.

There are different ways to grow artificial meat, but most use adult stem cells from a live animal. For beef, a tiny muscle sample is taken from a cow, under local anaesthesia. The muscle is chopped into smaller pieces, using enzymes to digest it and release the stem cells.

In a huge vat called a bioreactor, the stem cells are immersed in a broth containing salts, vitamins, sugars and proteins, as well as growth factors. The oxygen-rich, temperature-controlled environment allows cells to multiply dramatically. The stem cells then differentiate into muscle fibres that bunch together, aided by scaffolding material. The meat is ready for processing or cooking in a matter of weeks.

Producing a thick piece of steak is still some way off, with minced meat far easier to replicate. 3D printing is one possible option for creating a juicy steak layer by layer, but this technology is still in its infancy.

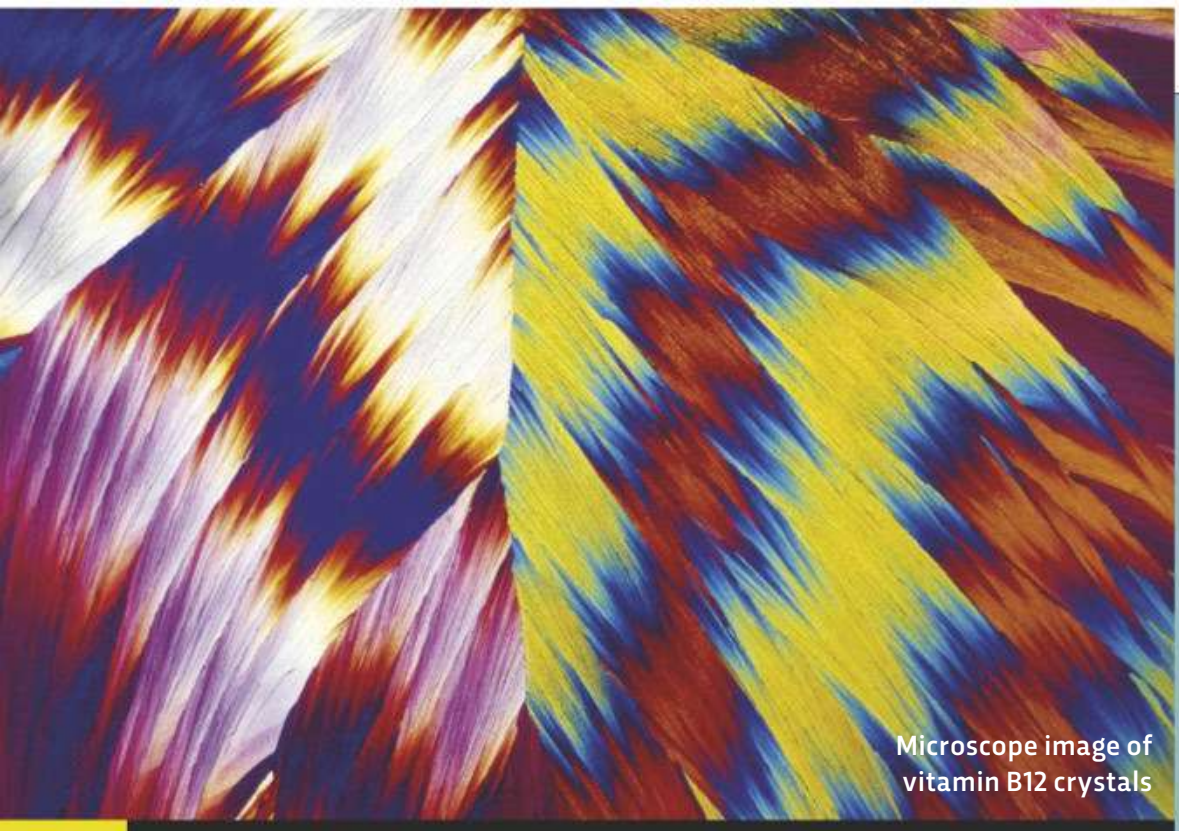
WILL ARTIFICIAL MEAT EVER TASTE AS GOOD AS THE REAL THING?

The first artificial beef burger (unveiled to great fanfare in 2013 and developed at a cost of €250,000) was reported to be rather dry and dense, consisting solely of muscle fibres.

A good meat replacement needs to mimic smell, texture and taste, which is no mean feat. In an animal, muscle comprises organised fibres, blood vessels, nerves, connective tissues and fat cells. Thousands of flavour molecules contribute to real meat's rich taste. It's possible to add synthetic flavours to artificial meat, but balancing and distributing them is tricky.

Progress has been made since 2013 and a Dutch company called Meatable now claims to be able to reprogram stem cells collected from bovine umbilical cord blood, turning them into master cells that can differentiate into fat or muscle. This allows muscle and fat cells to grow together as they do in animals. In theory, cells from different species could be grown together to create completely new flavours.

ALAMY X3, GETTY, SCIENCE PHOTO LIBRARY



Microscope image of vitamin B12 crystals

IS ARTIFICIAL MEAT SAFE?

Artificial meat is touted as being as safe or safer than the real thing, produced in a highly controlled environment.

It is highly unlikely to become contaminated with harmful bacteria such as *E. coli* because there are no digestive organs to worry about. With whole animals, there's always a risk of meat becoming contaminated with bacteria after slaughter.

Having said that, artificial meat producers do need to take extra care to keep everything sterile because the nutrient-rich environment in the bioreactors is a perfect breeding ground for bacteria.

Some people have raised concerns over the growth factors added to stem cells, which include hormones. These hormones are naturally present in animals as well as in real meat. However, overexposure can have adverse health effects in humans. This is why growth hormones have been banned in agriculture in the EU since 1981.

DOES ARTIFICIAL MEAT CONTAIN ENOUGH NUTRITION?

Artificial meat is packed with protein and newer versions also contain fat. The nutritional content can be controlled to a certain extent by adjusting fat levels and playing with the levels of saturated fatty acids and healthier polyunsaturated fatty acids. Saturated fats can be replaced with other types of fats, such as omega-3s, found naturally in fish or flaxseed oil. It's also possible to add extra micronutrients such as vitamin B12 to artificial meats, as is routinely done to breads and breakfast cereals.

The fact remains that eating too much red meat is bad for our health, increasing the risk of cardiovascular disease, type 2 diabetes and some cancers. With its controlled fat levels, artificial meat may be slightly healthier, but it would still need to be eaten in moderation.

Plant-based meat alternatives may be the healthiest option, with similar protein levels and lower levels of saturated fat compared to conventional meat burgers.

COULD ARTIFICIAL MEAT SAVE THE PLANET?

The global food system is under huge pressure from climate change, a growing population and increasing demand for animal products. As such, investors have poured vast sums into artificial meat start-ups in recent years. One estimate by US consultancy firm Kearney suggests that 35 per cent of all meat consumed globally will be cell-based by 2040.

Artificial meat can be produced faster and more efficiently than traditional meat, requiring a tiny fraction of the land. But it faces competition from insect-derived products and plant-based imitation meats, which consumers are already buying in increasing numbers.

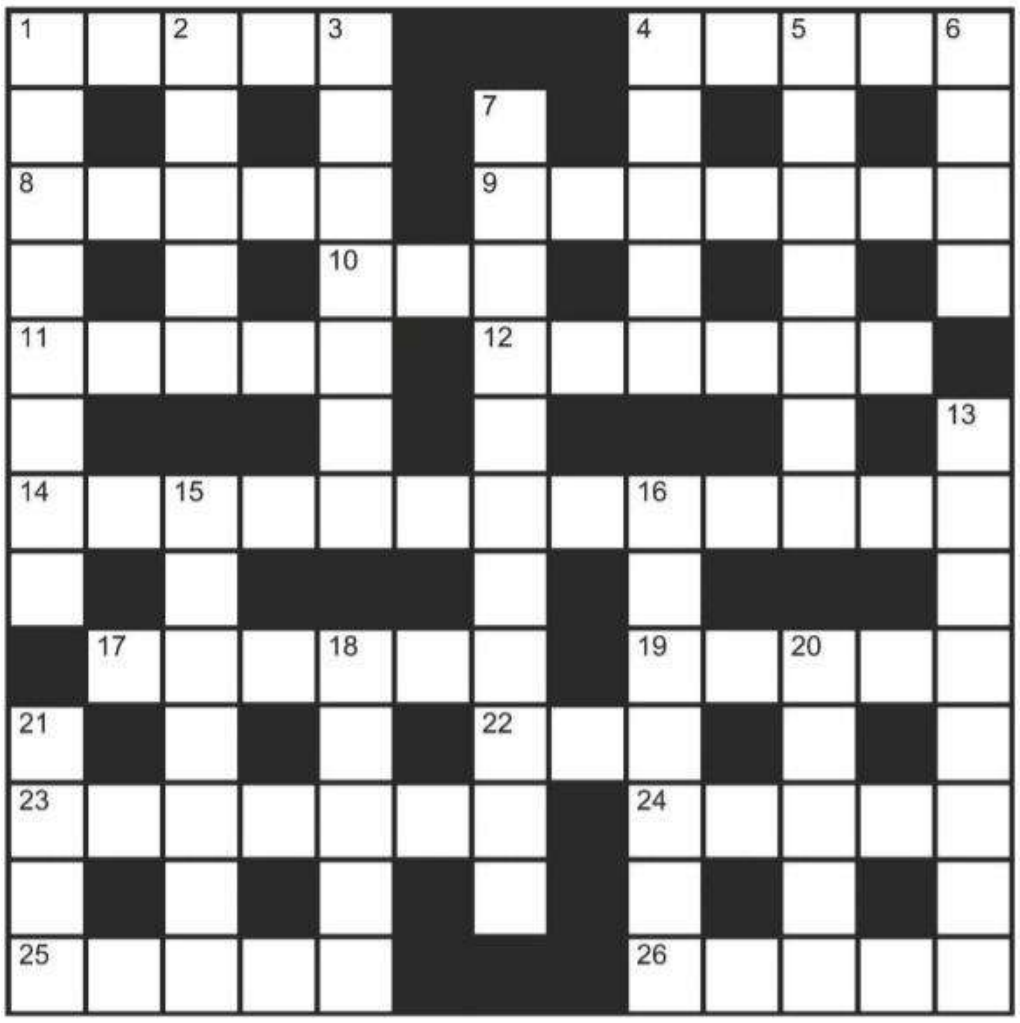
Livestock produce a big proportion of global greenhouse gas emissions. Large numbers of people switching to artificial meat, could lead to big cuts in these gases, particularly methane. But a study at Oxford University has suggested that the CO_2 emissions from powering artificial meat production facilities could be more damaging over the next 1,000 years.

by DR EMMA DAVIES

Emma is a science writer specialising in environment, food and toxicology.

CROSSWORD

GIVE YOUR BRAIN A WORKOUT



ACROSS

1 Clean land (5)
4 Avoid getting some confectionery (5)
8 Word about your first union contribution (5)
9 Ignorant woman joined conflict to the east (7)
10 Fool removes first slice of bread (3)
11 Returning old king managed to find holy book (5)
12 Overweight, that woman's relative (6)
14 Excellent landlord is a big character (7,6)
17 Sign of age, finding some bread on the internet (6)
19 Understood one during diplomacy (5)
22 Gamble without diamonds, and get diamonds (3)
23 Cosmetic for musical set (4,3)
24 Bird getting dressed, losing tail (5)
25 Strange omen about small particle (5)
26 Ocean unsuitable for such a vessel (5)

DOWN

1 Thrill, following team assistant (8)
2 Argumentative athlete? (5)
3 Bark time, holding single weapon (7)
4 Put additive in – don't eat a lot of food (5)
5 Local variation in citadel design (7)
6 Weapon used to acquire record points (4)
7 Animal invoice for Mr Cody (7,4)
13 Act makes others lose third in money (8)
15 Chopin's eccentric teaching method (7)
16 Join, in charge of the intestines (7)
18 Wife in the past getting new carriage (5)
20 Youngster on a new heel (5)
21 Fancy bearing that fellow (4)

ANSWERS

For the answers, visit **bit.ly/BBCFocusCW**
Please be aware the website address is case-sensitive.

J MARTIN/NORTHLAND COLLEGE

NEXT ISSUE

A NATURAL GLOW

Meet the animals who know how to shine.

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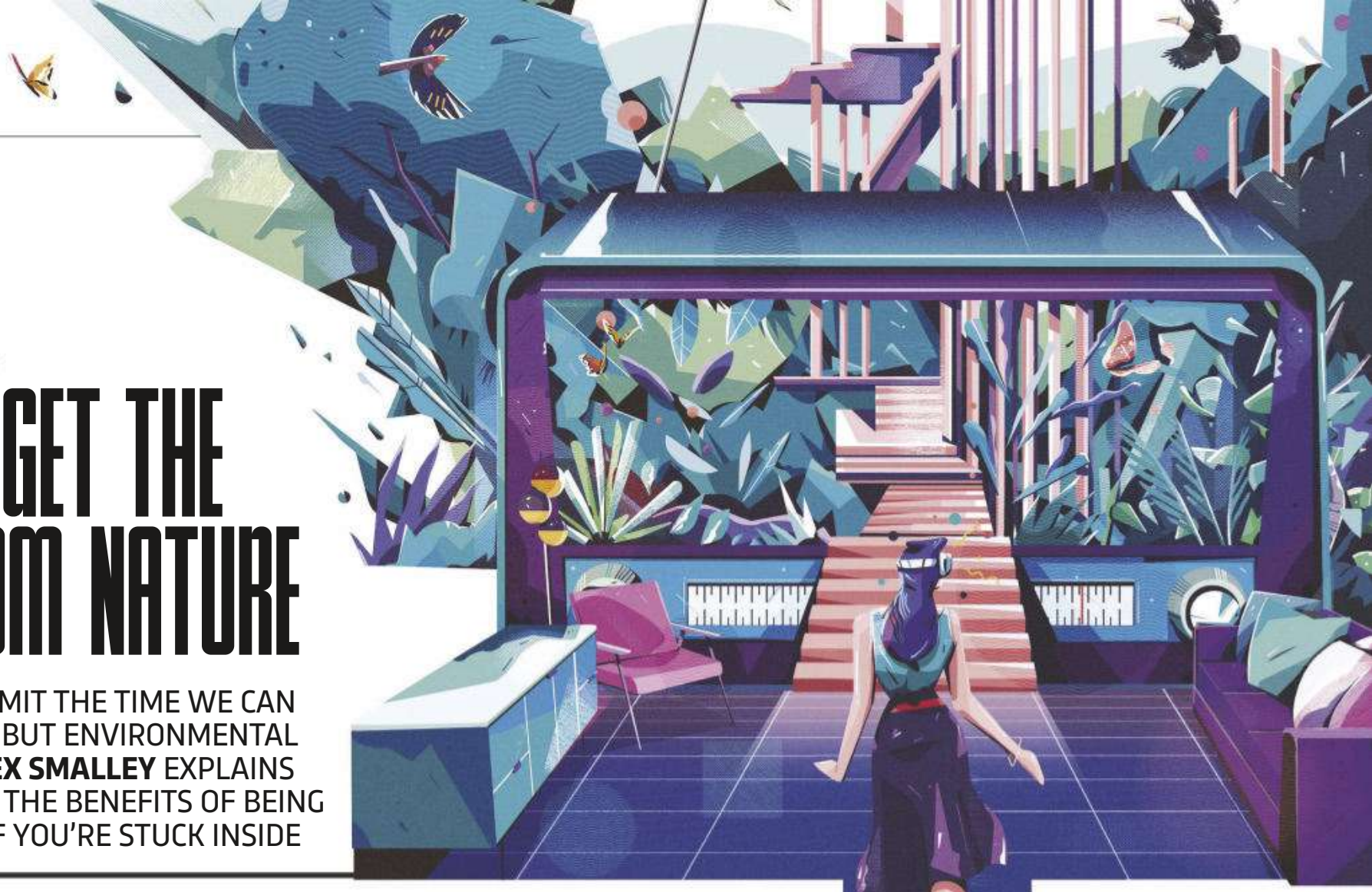
BBC TWO

Watch all the Mindful Moments from *Winterwatch* at **bit.ly/mindful-winter**



A SCIENTIST'S GUIDE TO LIFE

HOW TO GET THE BEST FROM NATURE

LOCKDOWN MAY LIMIT THE TIME WE CAN SPEND OUTDOORS, BUT ENVIRONMENTAL PSYCHOLOGIST **ALEX SMALLEY** EXPLAINS HOW YOU CAN GET THE BENEFITS OF BEING IN NATURE, EVEN IF YOU'RE STUCK INSIDE

NATURE IS GOOD FOR YOU

Studies prove this beyond doubt. We see biological markers of stress reduce and improvements in psychological wellbeing when people spend time in the natural world. Nature helps us to unwind after a difficult day. It can lead to an increase in positive emotions and a reduction in negative thought patterns, such as rumination. It's good for the environment too. Research suggests that people who feel more connected to nature are more likely to develop pro-environmental behaviour.

YOU DON'T NEED TO GO FAR

Nature is all around. Just look outside or open a window. Be purposeful. Take the time to stop, and really look and listen. You'll start to notice things that you never spotted before.

LISTENING TO NATURE IS LIKE A SUPERPOWER

When you walk past a hedgerow, you can't see the birds that are inside it. But if you learn to identify a few calls and then stop to listen, you might hear a wren, or a goldfinch, or a robin.

LINGER IN BLUE SPACES

Natural environments are made up of many elements. Our research is starting to tease out which of them are most beneficial. When you ask people what they value, blue spaces, such as lakes, rivers and oceans, score highly. Species richness is important too, as is birdsong. For me, nothing beats a blackbird on a rooftop at dusk. It instantly makes me feel at peace, and washes off the worst of the day.

VISIT SOMEWHERE AWESOME

It could help shrink your worries. Studies suggest that when we're in the presence of awe-inspiring nature, like a large waterfall or giant redwood, it can have a profound effect. It can make both you and your worries feel small, and promote altruistic behaviour.

IF YOU CAN'T GO OUT, TRY VIRTUAL NATURE

Over the last 12 months, as people have been less able to go out, we've been seeking out nature on TV, radio and online. *Winterwatch*'s Mindful Moments were very popular. I think virtual nature has therapeutic potential in its own right, so it's almost as if people have been self-medicating. Our Virtual Nature Experiment is looking at the effects of virtual nature on wellbeing. We know that if people are tired or stressed at the end of a day, these digital versions of nature can help them feel better.

LISTEN TO DIGITAL SOUNDSCAPES

When you close your eyes, you can travel anywhere, and it can be really relaxing. There's lots of content at the BBC's Soundscapes for Wellbeing website, including a sound effects archive that contains 33,000 sound recordings. So, if you want to kick back by listening to the birds of the Borneo rainforest, it's right there for you.

VIRTUAL NATURE ISN'T A SUBSTITUTE FOR THE REAL THING...

…but it still has a positive effect. I'm interested in how we can use these virtual experiences to help those who literally can't go out: people in care homes, patients recovering from surgery or NHS staff who work such long days that they don't get to go outside. We would love to bring this learning into those kinds of spaces.

MY TAKE-HOME MESSAGE?

Get out into nature if you can, but if you can't, try listening to a soundscape on your radio. It might just be the next best thing. **SF**

ALEX SMALLEY

Alex is a PhD student at the University of Exeter. Soundscapes for Wellbeing, including the Virtual Nature Experiment, can be found at ***bit.ly/VRnatureSF***

Interviewed by Dr Helen Pilcher.

NEED TO KNOW...

1

Getting outdoors and spending time in nature has measurable positive effects on your wellbeing.

2

Don't just rely on your eyesight, if you want to notice wildlife. Sound will often lead you to things you can't initially see.

3

Technology can bring the outdoors in, with beneficial effects. Recorded or simulated nature is nearly as good as the real thing.

ILLUSTRATION: JOE WALDRON

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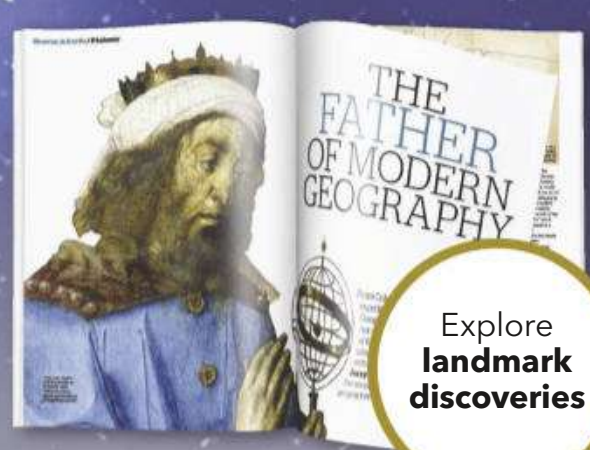

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